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DEVELOPMENT OF CRITERIA FOR MONITORING OF AIRPORT GROUND POLLUT--ETC(U)  
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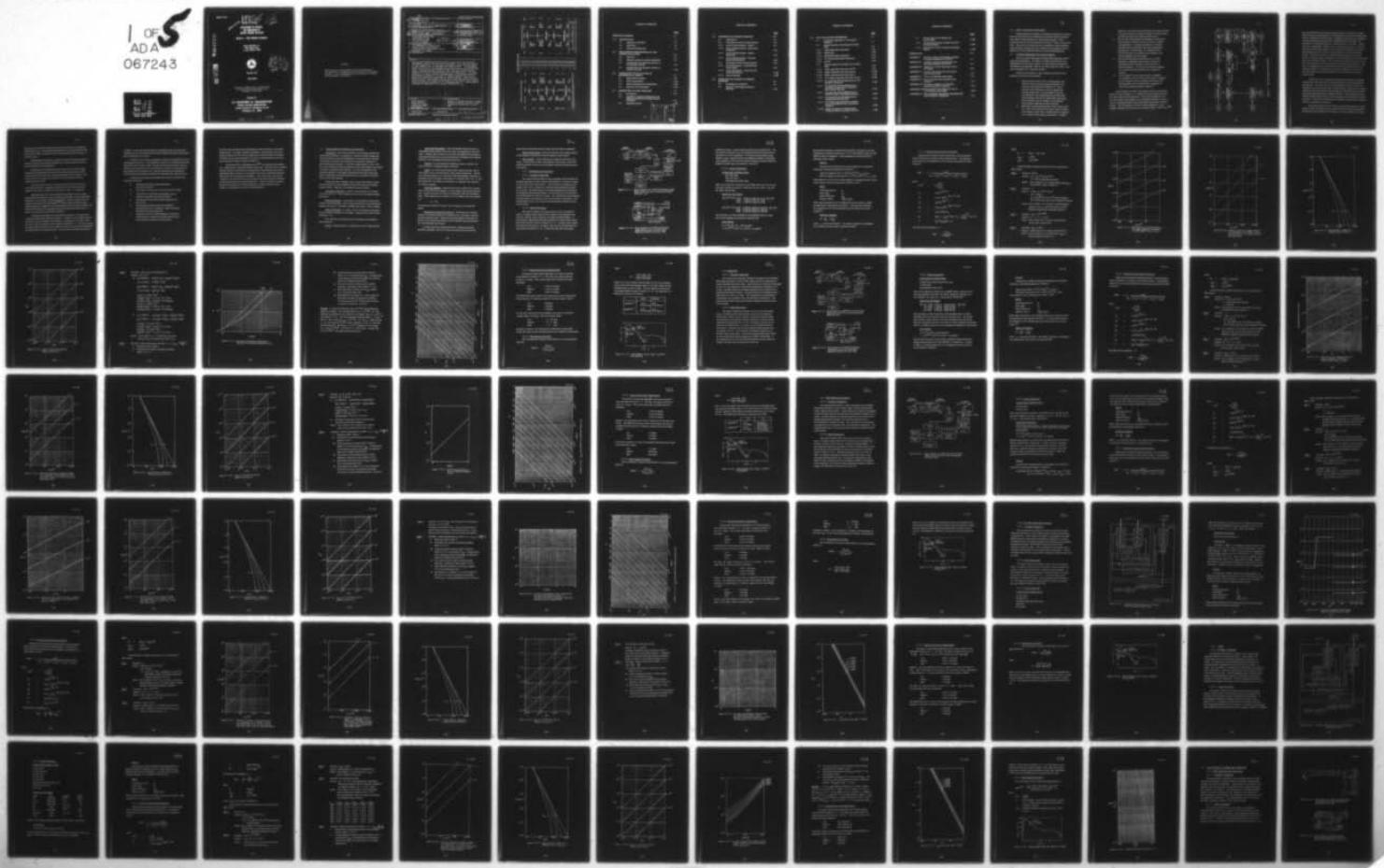
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**DEVELOPMENT OF CRITERIA  
FOR MONITORING OF  
AIRPORT GROUND POLLUTION**

**Volume II - Data Validation Procedures**

AD A0 67246

Science Applications, Inc.  
1200 Prospect Street  
La Jolla, California 92038



November 1978



**DDC FILE COPY**

**FINAL REPORT**

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Prepared for

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FEDERAL AVIATION ADMINISTRATION  
Systems Research & Development Service  
Washington, D.C. 20590**

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## Technical Report Documentation Page

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15. Abstract Criteria are developed by which the validity of pollution predictions and measurements in the airport environs can be judged. The criteria are applied to three technologies: (1) predictive mathematical models, (2) measurements by point samplers, and (3) measurements by remote monitors. For mathematical models the criterion is the agreement between predicted and measured pollution levels. Various mathematical models are described, analyzed and ranked by weighted attributes as screening models and as validation models. For point samplers, the criteria have been developed based on EPA-approved measurement principles and procedures for testing performance characteristics and for determining a consistent relationship to reference methods. Remote monitors belong to an evolving technology that has not yet been approved as to measurement principles. Thus criteria are developed to select certain remote sensing systems as potential candidates for air enforcement monitors. Data validation procedures are developed for the selected remote monitors.		
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**Approximate Conversions to Metric Measures**

Symbol	When You Know	Multiply by	To Find	Symbol
<b>LENGTH</b>				
inches	*12.5	centimeters	millimeters	in
feet	.30	centimeters	0.4	inches
yards	0.9	meters	3.3	feet
miles	1.6	kilometers	1.1	yards
			0.5	miles
<b>AREA</b>				
square inches	6.5	square centimeters	0.16	square inches
square feet	0.09	square meters	1.2	square yards
square yards	0.8	square kilometers	0.4	square miles
square miles	2.5	hectares ( $10,000 \text{ m}^2$ )	2.5	acres
<b>MASS (weight)</b>				
ounces	28	grams	0.035	ounces
pounds	0.45	kilograms	2.2	pounds
short tons (2000 lb)	0.9	tonnes (1000 kg)	1.1	short tons
<b>VOLUME</b>				
teaspoons	5	milliliters	0.03	fluid ounces
tablespoons	15	milliliters	2.1	pints
fluid ounces	.30	liters	1.06	quarts
cups	0.24	liters	0.26	gallons
pints	0.47	cubic meters	36	cubic feet
quarts	0.95	cubic meters	1.3	cubic yards
gallons	3.6			
cubic feet	0.03			
cubic yards	0.76			
<b>TEMPERATURE (exact)</b>				
Fahrenheit temperature	$\frac{5}{9}$ (after subtracting 32)	Celsius temperature	$^{\circ}\text{C}$	

**METRIC CONVERSION FACTORS**

**Approximate Conversions from Metric Measures**

Symbol	When You Know	Multiply by	To Find	Symbol
<b>LENGTH</b>				
mm		mm	in	in
cm		centimeters	0.04	inches
m		meters	3.3	feet
km		kilometers	1.1	yards
			0.5	miles
<b>AREA</b>				
square centimeters		square centimeters	0.16	square inches
square meters		square meters	1.2	square yards
square kilometers		square kilometers	0.4	square miles
hectares ( $10,000 \text{ m}^2$ )		hectares ( $10,000 \text{ m}^2$ )	2.5	acres
<b>MASS (weight)</b>				
grams		grams	0.035	ounces
kilograms		kilograms	2.2	pounds
tonnes (1000 kg)		tonnes (1000 kg)	1.1	short tons
<b>VOLUME</b>				
milliliters		milliliters	0.03	fluid ounces
liters		liters	2.1	pints
liters		liters	1.06	quarts
liters		liters	0.26	gallons
cubic meters		cubic meters	36	cubic feet
cubic meters		cubic meters	1.3	cubic yards
<b>TEMPERATURE (exact)</b>				
$^{\circ}\text{C}$		Celsius temperature	$^{\circ}\text{C}$	
$^{\circ}\text{F}$		Fahrenheit temperature	$^{\circ}\text{F}$	
<b>TEMPERATURE (exact)</b>				
$^{\circ}\text{C}$		Celsius temperature	$^{\circ}\text{C}$	
$^{\circ}\text{F}$		Fahrenheit temperature	$^{\circ}\text{F}$	

\*1 in = 2.54 centimeters. For other exact conversions and more detailed tables, see NBS Metric. Publ. 286, Units of Weights and Measures, Price \$2.25, SD Catalog No. C13.10286.

\*\* $^{\circ}\text{C}$  =  $\frac{5}{9}$  ( $^{\circ}\text{F}$  minus 32).

\*\*\* $^{\circ}\text{F}$  =  $\frac{9}{5}$  ( $^{\circ}\text{C}$  plus 32).

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## 7.0 DATA VALIDATION PROCEDURES

The procedures formulated in this Section constitute the criteria that will allow the FAA to methodically interrogate remote monitored data, taken for R&D and future air enforcement purposes. There are general procedures that apply to all systems. These are described first. Then there are special procedures applying to those individual remote monitor systems that were selected to be potentially useful in Section 6.2.2 for the R&D and future air enforcement applications.

### 7.1 Procedures Applicable to All Remote Monitors

There is a basic differentiation between R&D application and air enforcement application. For R&D, the monitor does not have to be designated as an "equivalent method", but must fulfill some specified performance requirements, while for air enforcement the monitor must only be designed as an "equivalent method".

The basic interrogation or data validation procedures can be phrased in the form of five questions:

1. Has the remote monitor that is collecting data in the vicinity of an airport been selected according to the selection criteria outlined in Section 6.0? There exist two major differences in the two applications: For R&D monitoring, the remote data do not need to be relatable to the standards, and eye safety limits can be relaxed, while for air enforcement monitoring, the remote data must be relatable to the standards and eye safety regulations must be observed.
2. What is the theoretical performance of the remote monitor? This can be answered by a step-by-step calculation of the signal-to-noise ratio, assuming known or optimum, e.g., detector-noise-limited, parameters. For R&D

application, the results of the calculation will indicate whether or not the instrument is sensitive enough in the concentration and distance range for the intended measurement.

3. Has the instrument fulfilled the equivalency requirement?

This question is relevant only for the future air enforcement application. If present procedures are followed, only data taken by individual instruments designated by manufacturer, model number, etc. and approved by the EPA and notice of acceptance duly published in the Federal Register need be accepted.

4. Have field calibrations been performed? For R&D

application, established experimental practices of calibrating should be followed, namely as often as deemed necessary. For future air enforcement application, calibration before and after data collection is required.

5. Is the operator(s) of the remote monitor competent?

The complexity of the remote monitors make it mandatory that the operator must be competent and familiar with the instrument, since it will be nearly impossible to make these complex machines "foolproof".

A logic diagram for a basic interrogation or data validation procedure is shown in Figure 7-1. It indicates the differentiation between air enforcement and R&D application. While the interrogation in the case of air enforcement appears more straightforward than for R&D, it is more demanding because of the requirement for demonstrating equivalency. The interrogation in the case of R&D application is more flexible, allowing even the use of a non-selected method. Nader et al. (229)

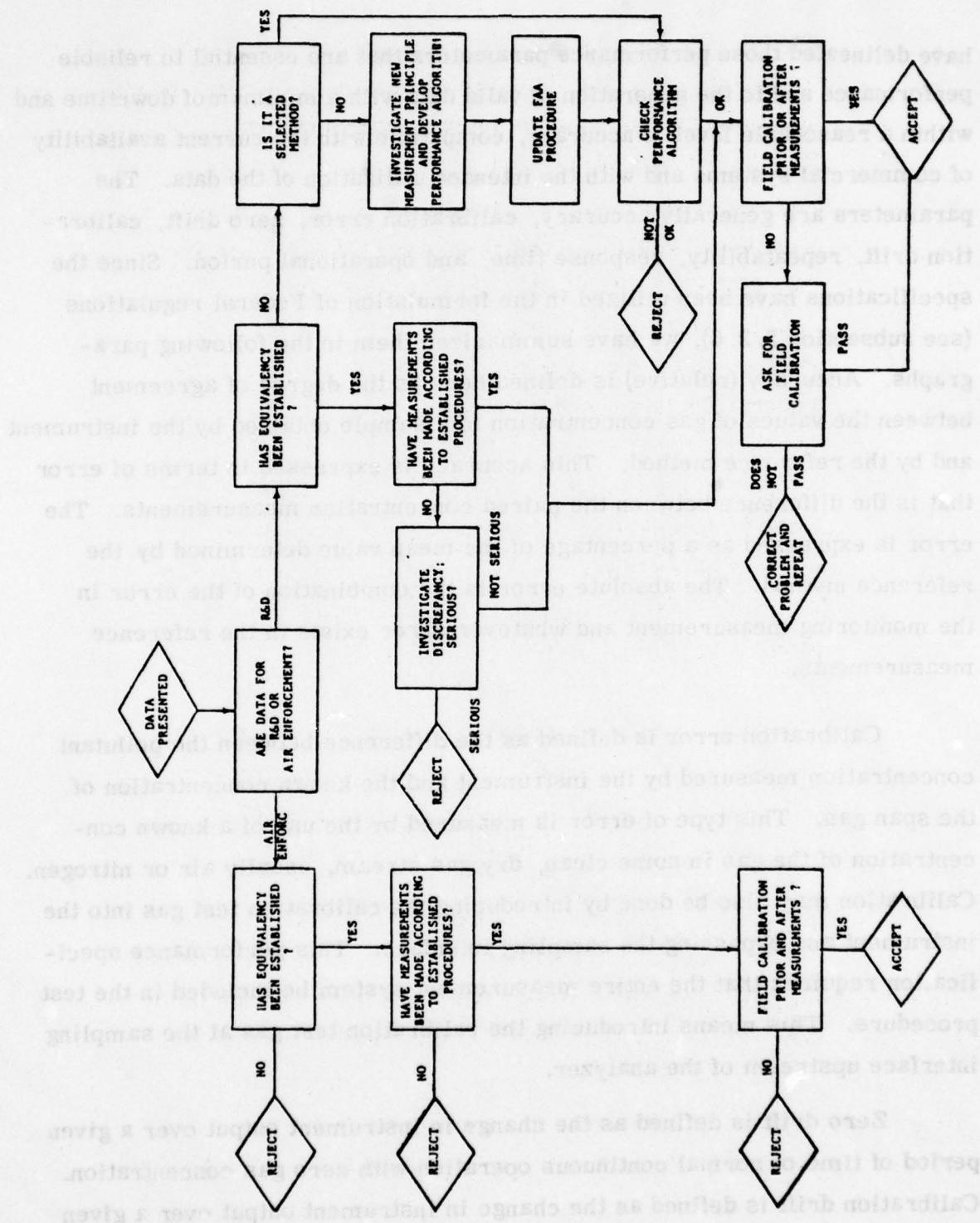


Figure 7-1. Data Interrogation and Validation.

have delineated those performance parameters that are essential to reliable performance and to the generation of valid data with a minimum of downtime and within a reasonable level of accuracy, compatible with the current availability of commercial systems and with the intended utilization of the data. The parameters are generally accuracy, calibration error, zero drift, calibration drift, repeatability, response time, and operational period. Since the specifications have been utilized in the formulation of Federal regulations (see subsection 3.2.6), we have summarized them in the following paragraphs. Accuracy (relative) is defined here as the degree of agreement between the values of gas concentration of a sample obtained by the instrument and by the reference method. This accuracy is expressed in terms of error that is the difference between the paired concentration measurements. The error is expressed as a percentage of the mean value determined by the reference method. The absolute error is the combination of the error in the monitoring measurement and whatever error exists in the reference measurements.

Calibration error is defined as the difference between the pollutant concentration measured by the instrument and the known concentration of the span gas. This type of error is measured by the use of a known concentration of the gas in some clean, dry gas stream, usually air or nitrogen. Calibration may also be done by introducing the calibration test gas into the instrument and bypassing the sampling interface. This performance specification requires that the entire measurement system be included in the test procedure. This means introducing the calibration test gas at the sampling interface upstream of the analyzer.

Zero drift is defined as the change in instrument output over a given period of time of normal continuous operation with zero gas concentration. Calibration drift is defined as the change in instrument output over a given

period of time of normal continuous operation when the gas concentration remains the same. Zero and calibration drift are critical parameters that have a direct effect on calibration error and ultimately on the accuracy of the data output.

Repeatability is defined as a measure of the measurement system's ability to give the same output reading(s) upon repeated measurements of the same pollutant concentration(s).

Response time is defined as the time interval from a step change in pollutant concentration at the input to the measurement system to the time at which 95 percent of the corresponding final value is reached. The response time of a measurement system is strongly influenced by the sampling approach used.

The operational period is a minimum period of time over which a measurement system is expected to operate within certain performance specifications without unscheduled maintenance, repair, or adjustment.

Although Nader et al. have specifically developed the performance specifications for stationary-source monitoring systems, they are applicable, in general, to other types of sampling situations. Thus we find that the conclusions reached by Dieck and Elwood<sup>(238)</sup> about emission analysis of gas turbine engines are supportive of the specifications as developed by Nader et al. Since Dieck and Elwood's conclusions are based on practical experience, we believe it is important to quote them verbatim.

"Without a knowledge of the measurement accuracy, the significance of observed differences cannot be assessed. In addition, the average emission level that a group of engines must achieve for compliance is a function of the accuracy of the measurement of the exhaust constituents; i. e., the less accurate the measurement, the lower the average level must be to assure that essentially all engines pass the compliance tests. The accuracy assessment specifically

## 7. If

included: 1) test instrument precision, 2) calibration gas accuracy and 3) sample error due to the distribution of data resulting from gas concentrations that are spatially non-uniform.

In addition, the accuracy assessment required the consideration of the following general topics: the propagation of errors in a calibration hierarchy, the proper choice of error units, surveys of instrument precision, the evaluation of the significance of various instrument errors, the assessment of the significance of sampling error, and the consideration of methods for demonstrating representative samples and improving instrument precision.

An accuracy assessment considering those factors resulted in the following conclusions:

1. Instrument precision is best expressed as percent of full scale.
2. The proper units for bias errors are percent of point.
3. Calibration-to-calibration repeatability may be utilized to estimate instrument precision.
4. Instrument precision shows wide variations from day-to-day.
5. Correcting past data by post-test calibration adjustments will not, in general, improve emission data altered by instrument drift.
6. Sampling error due to the distribution of emission concentrations in space is the single largest source of uncertainty in emission measurements.

All of the above provide some understanding of the uncertainty in emissions measurement. To ensure complete compliance, the emission control technology is required to reduce the average engine emissions below the Regulation limits by an amount equivalent to the sum of the uncertainty in the measurement and the engine to engine variability."

On the other hand, Klingenberg et al. (241) are critical of the present U. S. regulations for automobile exhaust emissions. They find that no allowance has been made for measuring uncertainties when evaluating the test results and that the final results are not subjected to any form of statistical analysis. They claim that unrecognized systematic errors can be big, but could be "avoided by currently performing correlation tests which should be required by law and specified in the Federal Register." These criticism are mainly directed to the particular influencing factors in emission tests for automobiles, but emphasize the need for standardization.

## 7.2 Remote Monitors Providing Line Profile Data

Introduction: The format employed in the following analyses has been chosen to provide to an engineer or scientist sufficient background, typical parameter values and methodology for this individual to perform a preliminary analysis of the suitability of a particular technique to a given measurement problem. It cannot be rigidly applied to every variation of any technique because development in instrument design may simplify (or further complicate) these analyses. It is the responsibility of the evaluation engineer to thoroughly understand the particular instrument under consideration; the following discussions are intended to provide a basis for that understanding.

Because the basic principles vary for these instruments, the discussion format also varies slightly to best suit the particular principle being presented. Basically, the following format is utilized.

Principles of Operation: A basic, brief description of the physical process involved. This is adapted from the more thorough discussion in Section 5.

System Description: A description of the equipment required and their interrelationship. This is often presented as a generalized block diagram plus photos or drawings of existing instruments, where available.

System Parameters: A listing of the more important parameters that the evaluation engineer will encounter, along with their typical values, availability, etc.

This is generally subdivided into the following (not all applies to each instrument).

Sources: Typically lasers or blackbody sources of radiant energy.

Operational Wavelengths: Those wavelength regions and the corresponding pollutant species which are known to be applicable to this technique. Because many of these are still under development (even though an operating instrument may have been built) future investigators will undoubtedly add to the wavelengths and species noted here.

Detector: Current applicable examples are given, however, the state-of-the-art is changing rapidly in this field.

Optics: All of these instruments require optical systems, and all such systems can be characterized by these several parameters. Calculation of these parameters for a particular instrument design--invariance of the quantity  $A\Omega$  at all points in the system is assumed here, but if this was neglected, the design performance is degraded and analysis can become complex.

Electronic Bandpass: Expressed as the time required for an instrument to reach 63 percent response to a step change in the measured parameter. Longer times have the effect of increasing the SNR by averaging the noise. When expressed as a frequency  $\Delta f$  it is related to the time constant  $t_c$  by

$$\Delta f = 1/4 t_c$$

The numerical constant 4 is typical, but will depend on the electronic design.

Theoretical Performance Prediction: This allows the evaluation engineer to determine whether the instrument can, in principle, perform the desired measurement. Optimum instrument design is assumed (e.g., detector noise limited performance) and any deviation from this optimum will cause degraded performance.

In many cases the required parameters, especially pollutant absorption constants, have not yet been determined and the theoretical

performance predictions cannot be made until these data are published.

Special Requirements: This calls attention to any unusual aspects of the technique to which the evaluation engineer must be aware.

Data Analysis: A basic technique for analysis of the data is presented. This provides a basic understanding of the problem; actual data analysis generally involves more atmospheric parameters than this basic presentation.

#### 7. 2. 1 LWIR Differential Absorption

##### 7. 2. 1. 1 Principle of Operation

The measurement principle of long wavelength infrared (LWIR) differential absorption is used to obtain concentrations as a function of range for ozone and certain hydrocarbons. Laser pulses at two different wavelengths in the 8-12  $\mu\text{m}$  region are emitted and the backscattered signals are recorded. By differencing the wavelength-dependent and ratioing the time-dependent backscattered signals, the transmission of the pollutants can be determined as a function of range. The concentration of the pollutant is proportional to the logarithm of the monochromatic transmission. The proportionality factor is the monochromatic absorption coefficient which must be known.

##### 7. 2. 1. 2 System Description

The system consists of an energy source of one or two pulsed lasers, an optical system which may be common to the transmitter and receiver, and the receiver detector, electronics and data display. A block diagram indicating the essential elements of a typical system using direct detection (dd) is shown in Figure 7. 2. 1-1. In order to use a heterodyne detection (hd) system, a frequency shift must be provided within the instrument (see Figure 7. 2. 1-2. It should be noted that no prototype

7.2.1.2b

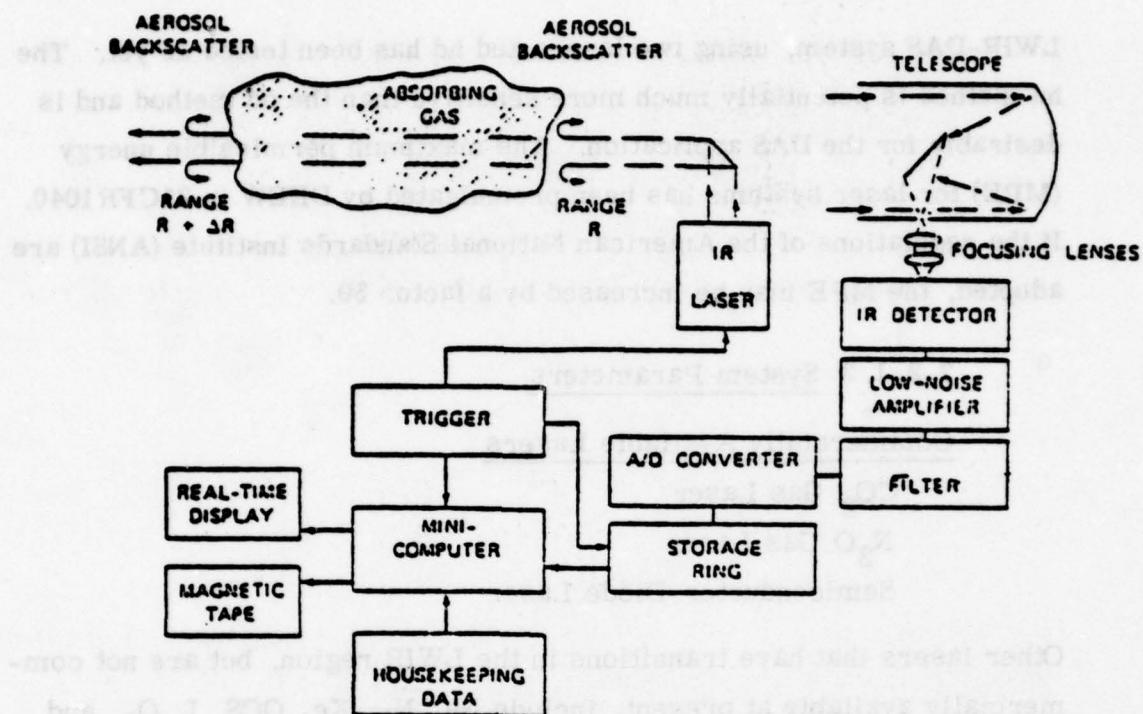


Figure 7.2.1-1. Block Diagram for LWIR DAS System Using Single Laser and Direct Detection (adopted from Ref. 249).

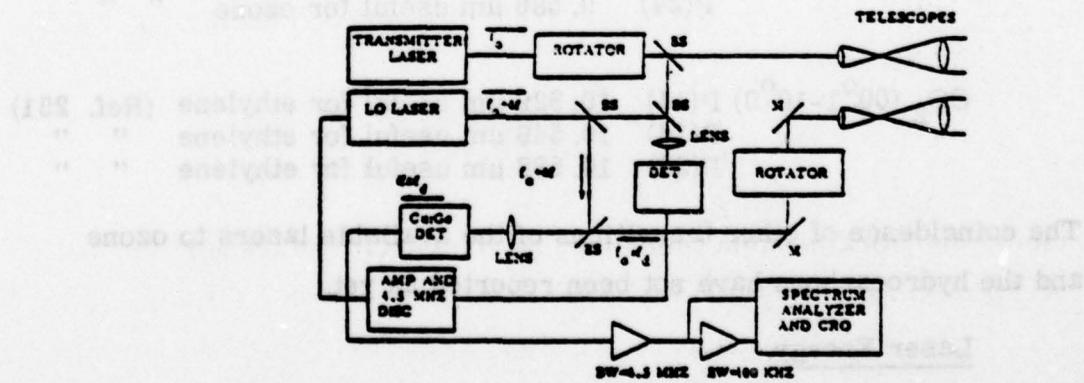


Figure 7.2.1-2. Block Diagram for LWIR DAS System Using Single Laser and Heterodyne Detection (adopted from Ref. 258).

7.2.1.2c  
7.2.1.3a

LWIR-DAS system, using two lasers and hd has been tested as yet. The hd method is potentially much more sensitive than the dd method and is desirable for the DAS application. The maximum permissible energy (MPE) for laser systems has been promulgated by DHEW in 21CFR1040. If the regulations of the American National Standards Institute (ANSI) are adopted, the MPE may be increased by a factor 50.

### 7.2.1.3 System Parameters

#### Commercially Available Lasers

$\text{CO}_2$  Gas Laser

$\text{N}_2\text{O}$  Gas Laser

Semiconductor-Diode Laser

Other lasers that have transitions in the LWIR region, but are not commercially available at present, include Ne,  $\text{N}_2$ , Xe, OCS, I,  $\text{O}_2$ , and HF (Refs. 256 and 257).

#### Operational Wavelengths

$\text{CO}_2$  ( $00^{\circ}1-02^{\circ}0$ ) P(14)     $9.504 \mu\text{m}$  useful for ozone (Ref. 251)  
P(20)     $9.552 \mu\text{m}$  useful for ozone    "    "  
P(24)     $9.586 \mu\text{m}$  useful for ozone    "    "

$\text{CO}_2$  ( $00^{\circ}1-10^{\circ}0$ ) P(14)     $10.529 \mu\text{m}$  useful for ethylene (Ref. 251)  
P(16)     $10.549 \mu\text{m}$  useful for ethylene    "    "  
P(20)     $10.588 \mu\text{m}$  useful for ethylene    "    "

The coincidence of other transitions of the available lasers to ozone and the hydrocarbons have not been reported as yet.

#### Laser Energy

$2 \times 10^{-4} \text{ J/cm}^2$  for 1-100 ns pulses  
 $1.1 \times 10^{-2} t^{1/4} \text{ J/cm}^2$  for 100 ns - 10 s pulses

Shortest pulse duration of commercially available CO<sub>2</sub> lasers is 40 nsec, resulting in a resolution element  $\Delta L$ , of 6 m, and available energy exceeds MPE by orders of magnitude. ANSI regulations would permit 50 fold increase in laser energy.

#### Detector

Commercially available detectors with highest D\* and shortest risetimes at operating temperatures of 77K are

Lead-Tin-Telluride ( $D^* \sim 5 \times 10^{10} \text{ cm Hz}^{1/2}/W$ ,  $t_c \sim 10 \text{ ns}$ )

Mercury-Cadmium-Telluride ( $D^* \sim 3 \times 10^{10} \text{ cm Hz}^{1/2}/W$ ,  $t_c < 1 \text{ ns}$ )

These detectors can be made to peak anywhere in the region from 8-12  $\mu\text{m}$ . Active detector areas can range from 0.0025 to 1 mm<sup>2</sup>.

#### Optics

Collecting Aperture  $A_o$

Solid Angle  $\Omega_o$

Optical Efficiency  $\eta_{opt}$

Detector Optics  $A_d \Omega_d (= A_o \Omega_o)$

These optical parameters are variables that must be chosen to fulfill the operational requirements (see below). For heterodyne detection, the constraint for the coherent aperture must be taken into account ( $A_o \Omega_o \approx \lambda^2$ ).

#### Electronic Bandpass

$$\Delta f = \frac{1}{4t_c} = \frac{1}{4n t_s}$$

where  $t_s$  is the pulse duration. The number of pulses to be sampled is a variable that can be used to increase the SNR.

### 7.2.1.4a

#### 7.2.1.4 Theoretical Performance Prediction

Based upon the selected system parameters, the performance can be predicted for a detector-noise-limited system. The signal-to-noise ratio for the determination of the pollutant concentration by DAS is given by

$$\text{SNR} = \frac{\ln Q^1}{dP \sqrt{(1/P_1)^2 + (1/P'_1)^2 + (1/P_2)^2 + (1/P'_2)^2}}$$

where

$$\ln Q^1 = \ln \frac{P_1 P'_2}{P'_1 P_2}$$

$$P_1 = (G/R^2) e^{-2k_1 C R}$$

$$P'_1 = (G/(R + \Delta R))^2 e^{-2k_1 C (R + \Delta R)}$$

$$P_2 = (G/R^2) e^{-2k_2 C R}$$

$$P'_2 = (G/(R + \Delta R))^2 e^{-2k_2 C (R + \Delta R)}$$

$$G = \eta P_t \Delta R N(R) \beta A_o$$

$$dP = \text{NEP}/F = (A_d \Delta f)^{1/2} (D^*)^{-1}/F = \left( \frac{A_d}{4\pi \tau_s} \right)^{1/2} (D^*)^{-1}/F$$

$$F = \eta_Q \lambda^3 / 2 \Omega_d \sqrt{A_d B} hc D^*$$

The SNR may be simplified, i.e.,

$$\text{SNR} = \frac{Q P_{\text{eff}}}{2 \text{NEP}/F}$$

7.2.1.4b

where

$$Q = 2(k_1 C - k_2 C) \Delta R$$

$$P_{\text{eff}} = G \xi(R)$$

$$\xi(R) = R^{-2} e^{-2kCR}$$

In the following a stepwise description for the calculation of SNR is given

Step 1: Calculate: NEP/F

$$\text{Assume: } D^* = 3 \times 10^{10} \text{ cm Hz}^{1/2} \text{ W}^{-1}$$

$F \approx 100$  for heterodyne detection

Result: Plot in Figure 7.2.1-3 shows NEP/F versus  $A_d$  for different number of pulses  $n$ .

Step 2: Calculate: G

$$\text{Assume: } N(R)\beta \approx 8 \times 10^{-8} \text{ cm}^{-1} \text{ ster}^{-1}$$

$$\Delta R = 1500 \text{ cm}$$

$P_t = 2 \times 10^4 \text{ W}$  for a  $2 \times 10^{-3} \text{ J}$  laser, having a  $10 \text{ cm}^2$  beam area and a pulse duration of 100 nsec

Result: Plot in Figure 7.2.1-4 shows G versus receiver aperture area  $A_o$  for three values of overall efficiency (optical and mechanical shutters)

Step 3: Calculate:  $\xi(R) = R^{-2} e^{-2kCR}$

$$\text{Assume: } kC = 0, .3, 1, 3 \text{ km}^{-1}$$

Result: Plot in Figure 7.2.1-5 shows  $\xi(R)$  versus R for the above values of kC

Step 4: Calculate:  $P_{\text{eff}} = G \xi(R)$

Assume: Useful range of R between 100 and 1000 m

Result: Plot in Figure 7.2.1-6 which shows  $P_{\text{eff}}$  vs.  $\xi(R)$  for different values of G.

7.2.1.4c

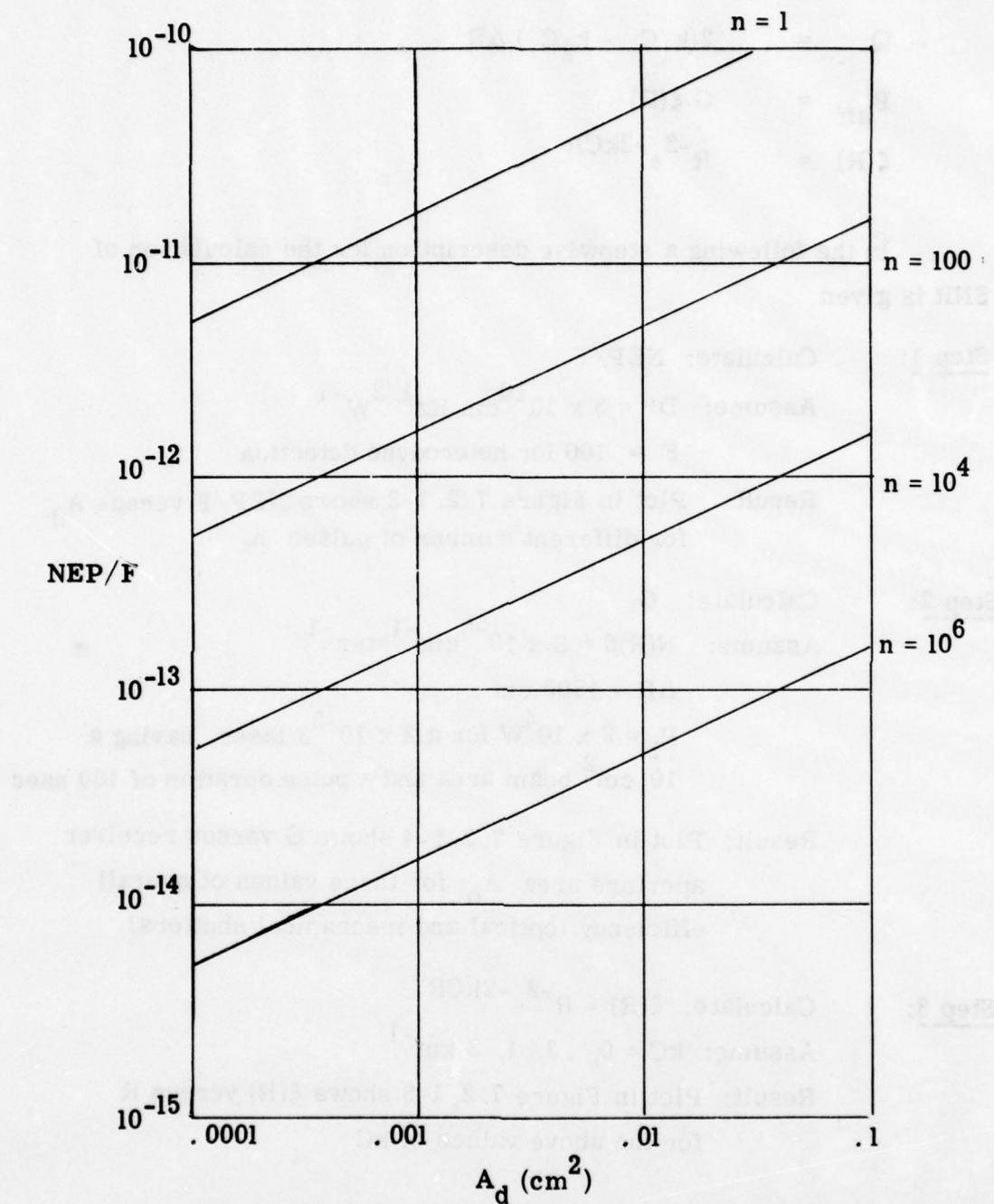


Figure 7.2.1-3. NEP versus  $A_d^2$  for Different Values of Number of Pulses, Assuming  $D^* = 3 \times 10^{10} \text{ cmH}_2\text{W}^{-1}$  and  $t_s = 100 \text{ ns}$ .

7. 2. 1. 4d

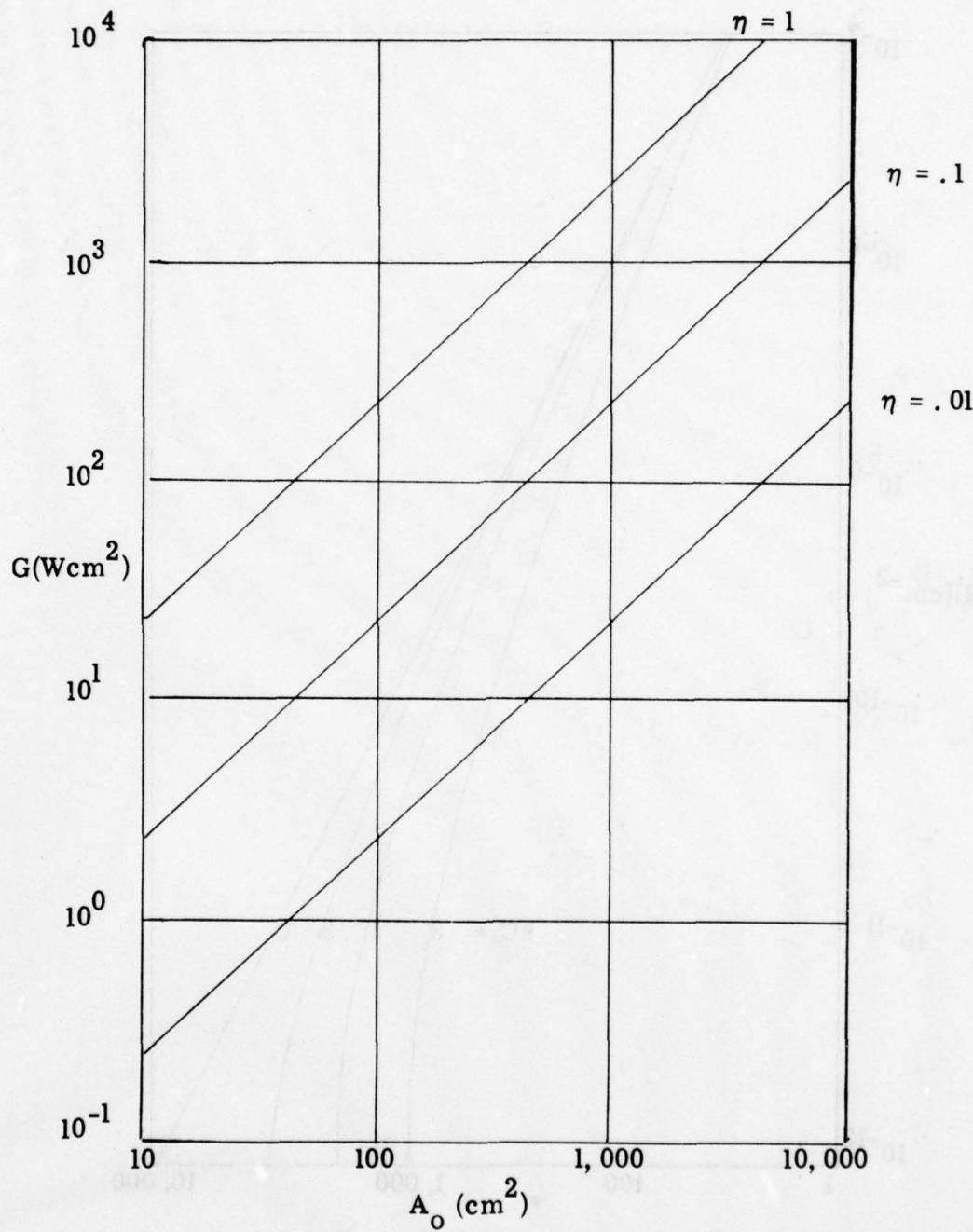


Figure 7. 2. 1-4. Function  $G$  versus  $A_0$  for Three Values of  $\eta$ , using  $\Delta R = 15$  m,  $N(R)\beta = 8 \times 10^{-8}$  cm<sup>-1</sup>ster<sup>-1</sup> and  $P_t = 2 \times 10^{-3}$  J for 10 cm<sup>2</sup> laser beam area.

7. 2. 1. 4e

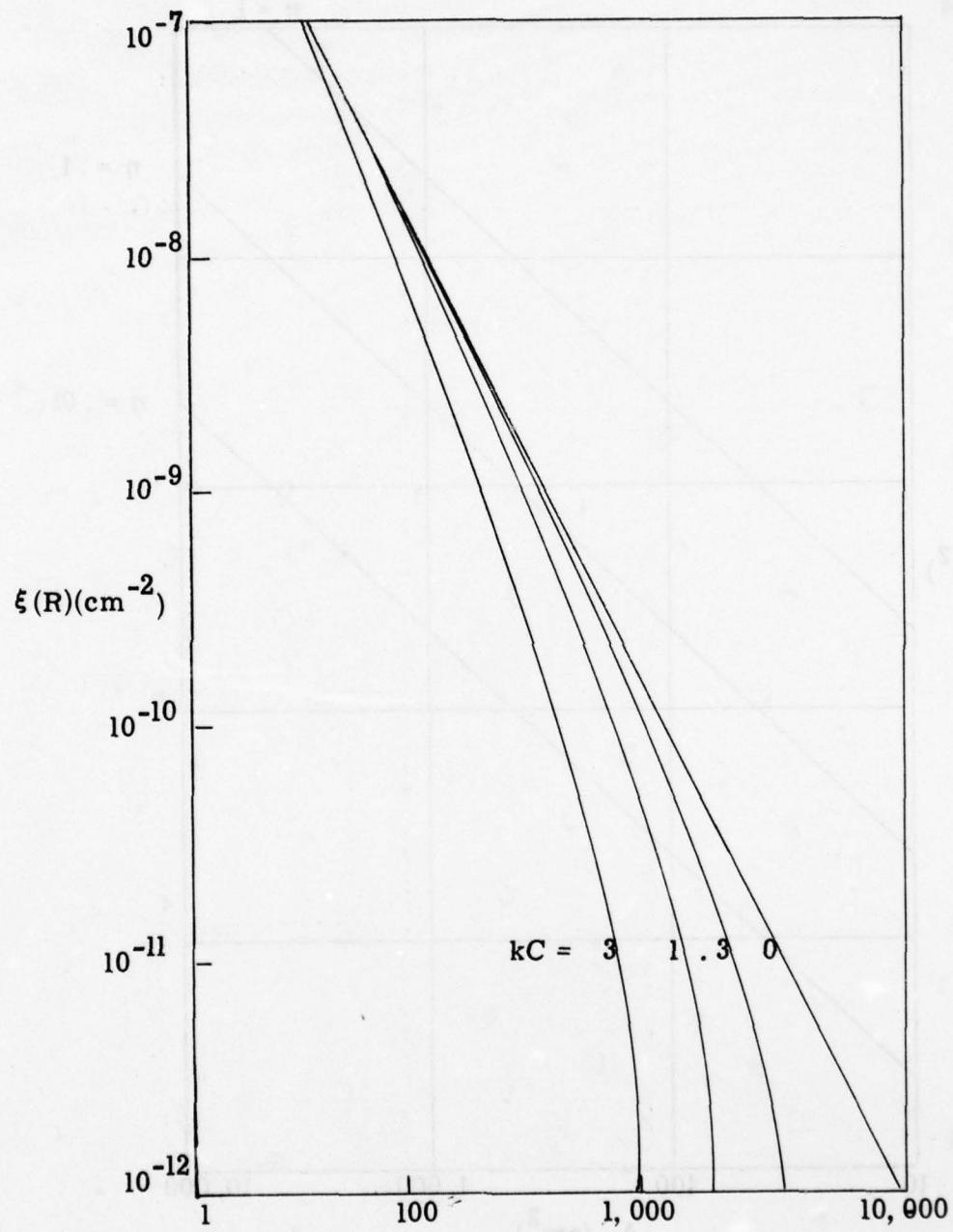


Figure 7. 2. 1-5. Function  $\xi(R)$  vs. Range for Different Values of  $kC$  (km<sup>-1</sup>)

7. 2. 1. 4f

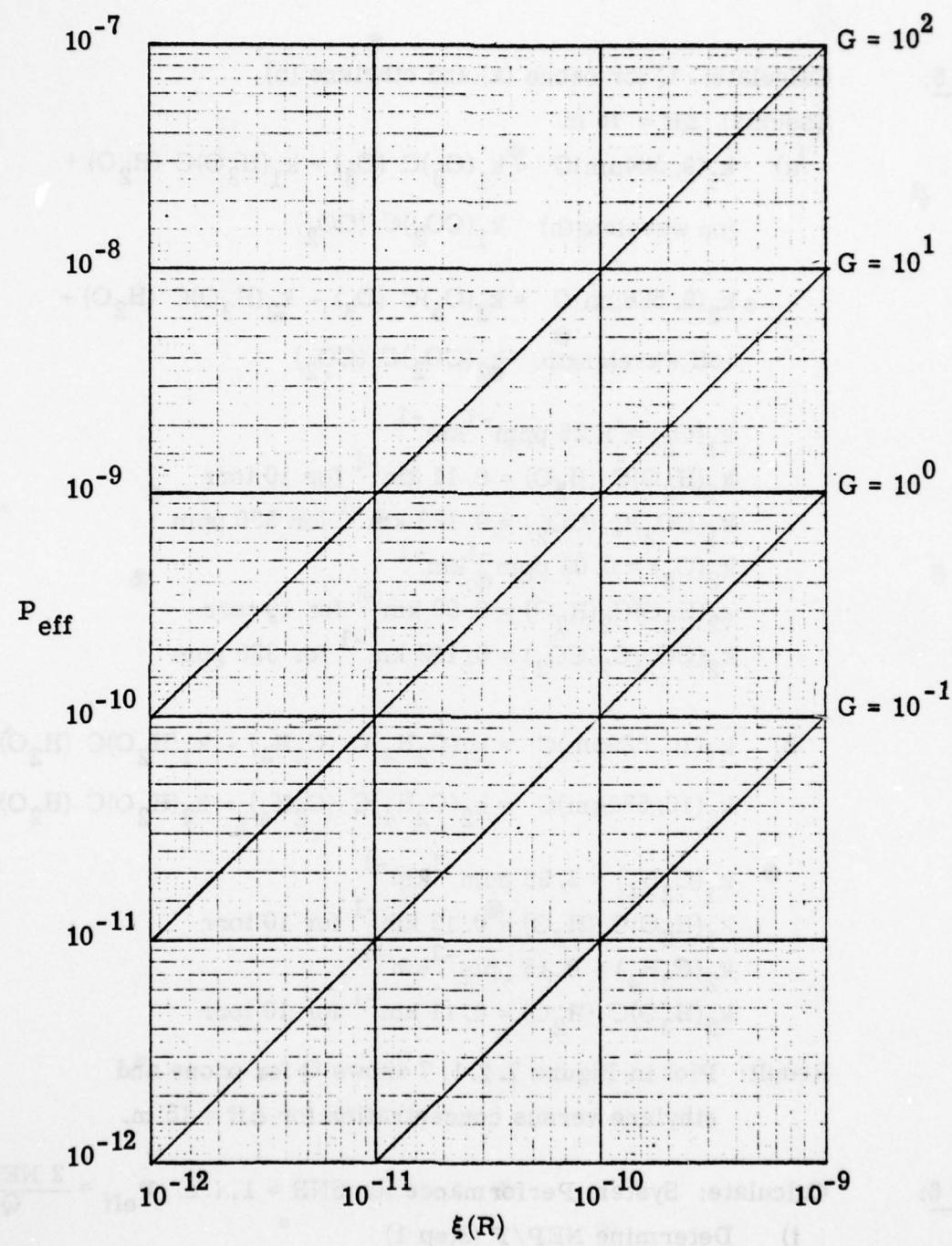


Figure 7. 2. 1-6.  $P_{\text{eff}}$  vs. the Function  $\xi(R)$  for Different Values of  $G$

Step 5: Calculate: Q for ozone (a) and ethylene (b)

Assume:  $\Delta R = 15 \text{ m}$

$$\text{a)} \quad k_1(9.504\mu\text{m})C = k_1(O_3)C (O_3) + k_1(H_2O)C (H_2O) + \\ (\text{on wavelength}) \quad k_1(CO_2)C (CO_2)$$

$$k_2(9.586\mu\text{m})C = k_2(O_3)C (O_3) + k_2(H_2O)C (H_2O) + \\ (\text{off wavelength}) \quad k_2(CO_2)C (CO_2)$$

$$k_1(O_3) = 1.25 \text{ ppm}^{-1}\text{km}^{-1}$$

$$k_1(H_2O)C (H_2O) = 0.11 \text{ km}^{-1} \text{ for } 10 \text{ torr}$$

$$k_1(CO_2)C (CO_2) = 0.123 \text{ km}^{-1} \text{ for } 330 \text{ ppm}$$

$$k_2(O_3) = 0.08 \text{ ppm}^{-1}\text{km}^{-1}$$

$$k_2(H_2O)C (H_2O) = 0.09 \text{ km}^{-1} \text{ for } 10 \text{ torr}$$

$$k_2(CO_2)C (CO_2) = 0.112 \text{ km}^{-1} \text{ for } 330 \text{ ppm}$$

$$\text{b)} \quad k_1(10.529\mu\text{m})C = k_1(C_2H_4)C (C_2H_4) + k_1(H_2O)C (H_2O)$$

$$k_2(10.588\mu\text{m})C = k_2(C_2H_4)C (C_2H_4) + k_2(H_2O)C (H_2O)$$

$$k_1(C_2H_4) = 2.98 \text{ ppm}^{-1}\text{km}^{-1}$$

$$k_1(H_2O)C (H_2O) = 0.12 \text{ km}^{-1} \text{ for } 10 \text{ torr}$$

$$k_2(C_2H_4) = 0.15 \text{ ppm}^{-1}\text{km}^{-1}$$

$$k_2(H_2O)C (H_2O) = 0.11 \text{ km}^{-1} \text{ for } 10 \text{ torr}$$

Result: Plot in Figure 7.2.1.7 shows Q for ozone and ethylene versus concentration for  $\Delta R = 15 \text{ m}$ .

Step 6:

Calculate: System Performance for SNR = 1, i.e.,  $P_{\text{eff}} = \frac{2 \text{ NEP/F}}{Q}$

i) Determine NEP/F (Step 1)

ii) Calculate Q for desired concentration (Step 5,  
Figure 7.2.1-7)

7. 2. 1. 4h

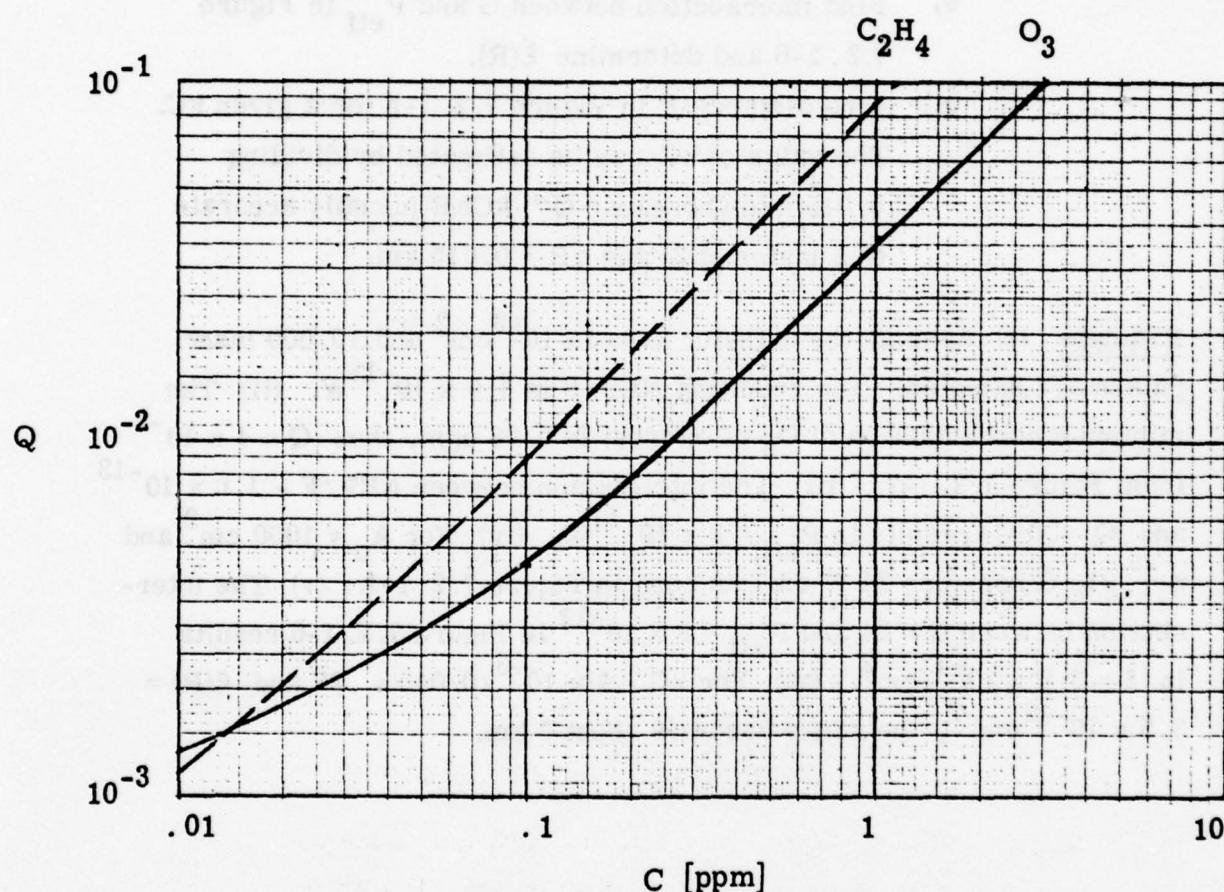


Figure 7.2.1-7.  $Q$  versus Concentration of Ozone and Ethylene for a Resolution Element of 15 m.

- iii) Locate intersection between  $\text{NEP}/F$  and  $Q$  in Figure 7.2.1-8 and determine  $P_{\text{eff}}$ . If intersection is not within the limits of the graph, the measurement is not feasible beyond 100 m.
- iv) For a given receiver optics area and overall efficiency, determine  $G$  from Figure 7.2.1-4.
- v) Find intersection between  $G$  and  $P_{\text{eff}}$  in Figure 7.2.1-6 and determine  $\xi(R)$ .
- vi) Find distance  $R$  in Figure 7.2.1-5 for a given  $kC$ . The value of  $kC$  may be estimated by dividing 0.015 into  $Q$  because  $Q \approx kC\Delta R$  (usually accurate to a factor of 2) and  $\Delta R = 0.015$  km.

Example (i) Assume the detector area is  $10^{-3} \text{ cm}^2$  and 10,000 laser pulses are sampled. The resulting  $\text{NEP}/F$  is  $1.6 \times 10^{-13} \text{ W}$ . (ii) The minimum concentration of  $O_3$  of interest is 0.08 ppm, thus  $Q = 4 \times 10^{-3}$  from Figure 7.2.1-7. (iii) The intersection between  $\text{NEP}/F = 1.6 \times 10^{-13}$  and  $Q = .004$  results in  $P_{\text{eff}} = 8 \times 10^{-11} \text{ W}$ . (iv) For  $A_o = 1000 \text{ cm}^2$  and  $\eta = .01$ ,  $G$  becomes  $24 \text{ W cm}^{-2}$  as seen in Figure 7.2.1-4. (v) The intersection between  $G = 24$  and  $P_{\text{eff}} = 8 \times 10^{-11}$  in Figure 7.2.1-6 results in  $\xi = 3.5 \times 10^{-12} \text{ cm}^2$ . (vi) For  $kC = 4 \times 10^{-3}/0.015 = .27$  and  $\xi(R) = 3.5 \times 10^{-12} \text{ cm}^{-2}$ , the range becomes about 3 km.

7. 2. 1. 4j

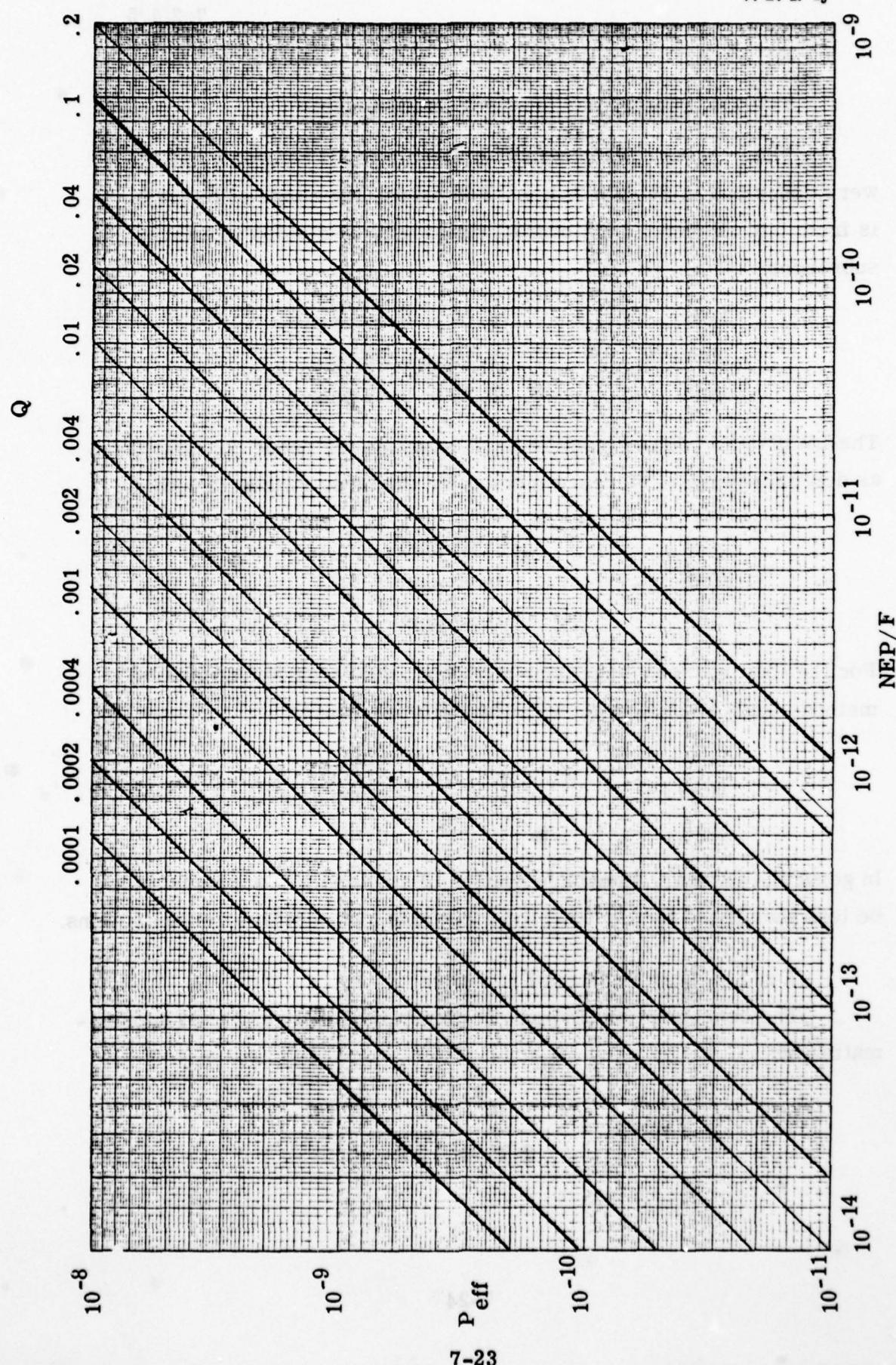


Figure 7.2.1-8.  $P_{\text{eff}}$  versus  $NEP/F$  for Different Values of  $Q$ .

7.2.1.5  
7.2.1.6a

#### 7.2.1.5 Special Performance Requirements

The general requirements applicable to all remote monitors were described in Section 7.1.1. For ozone, the range of interest is from 0 to .5 ppm. This overall range may be divided into three subranges:

Low	0.06 to 0.10 ppm
Medium	0.15 to 0.25 ppm
High	0.35 to 0.45 ppm

The LWIR-DAS remote monitor must measure the ozone concentration as determined by a reference method for the three ranges to within

Low	0.02 ppm
Medium	0.03 ppm
High	0.04 ppm

For the total hydrocarbons (non-methane), the range for automated methods ought to be 2 ppm, with the following ranges

Low	.2 - .28 ppm
Medium	.5 - .6 ppm
High	1 - 2 ppm

In general, however, the concentration of ethylene will appreciably be less than those for the total hydrocarbons/non-methane concentrations.

#### 7.2.1.6 Data Analysis Procedure

The concentration (in ppm) is determined in a very good approximation by

$$C(ppm) = \frac{10^6 \ln Q}{2 (k_1 - k_2) \Delta R}$$

### 7.2.1.6b

where

$$Q = \frac{P_1(R) P_2(R + \Delta R)}{P_1(R + \Delta R) P_2(R)}$$

Figure 7.2.1-9 is a typical received signal from the on-wavelength (lower curve) and off-wavelength (upper curve) laser beams with the abscissa shown in units of range. The four signals are determined from analog signals as given in Figure 7.2.1-9. The absorption coefficients  $k_1$  and  $k_2$  are as follows:

	Ozone	Ethylene
$k_1(\text{ppmkm})^{-1}$	1.25 @ 9.504 $\mu\text{m}$	2.98 @ 10.529 $\mu\text{m}$
$k_2(\text{ppmkm})^{-1}$	0.08 @ 9.586 $\mu\text{m}$	0.15 @ 10.588 $\mu\text{m}$

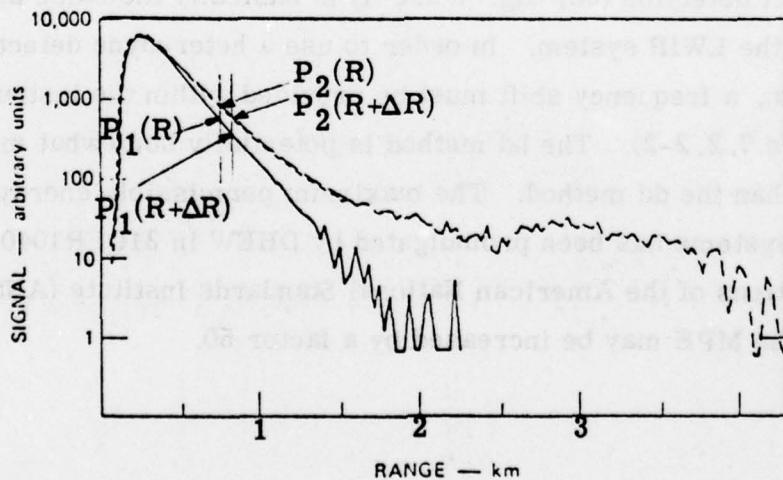


Figure 7.2.1-9. Analog Signals  $P_1(R)$ ,  $P_2(R)$ ,  $P_1(R + \Delta R)$  and  $P_2(R + \Delta R)$

### 7. 2. 2 MWIR-DAS

#### 7. 2. 2. 1 Principle of Operation

The measurement principle of medium wavelength infrared (MWIR) differential absorption is used to obtain range-resolved concentrations of carbon monoxide and nitrous oxide. Laser pulses at two different wavelengths in the 4.8-5.4  $\mu\text{m}$  region are emitted and the backscattered signals are recorded. By differencing the wavelength-dependent and ratioing the time-dependent backscattered signals, the transmission of the pollutants can be determined as a function of range. The concentration of the pollutant is proportional to the logarithm of the monochromatic transmission. The proportionality factor is the monochromatic absorption coefficient which must be known.

#### 7. 2. 2. 2 System Description

The system consists of an energy source of one or two pulsed lasers, an optical system which may be common to the transmitter and receiver, and the receiver detector, electronics and data display. A block diagram indicating the essential elements of a typical system using direct detection (dd) (fig. 7.2.2-1) is basically the same as was shown for the LWIR system. In order to use a heterodyne detection (hd) system, a frequency shift must be provided within the instrument (see Figure 7.2.2-2). The hd method is potentially somewhat more sensitive than the dd method. The maximum permissible energy (MPE) for laser systems has been promulgated by DHEW in 21CFR1040. If the regulations of the American National Standards Institute (ANSI) are adopted, the MPE may be increased by a factor 50.

7.2.2.2b

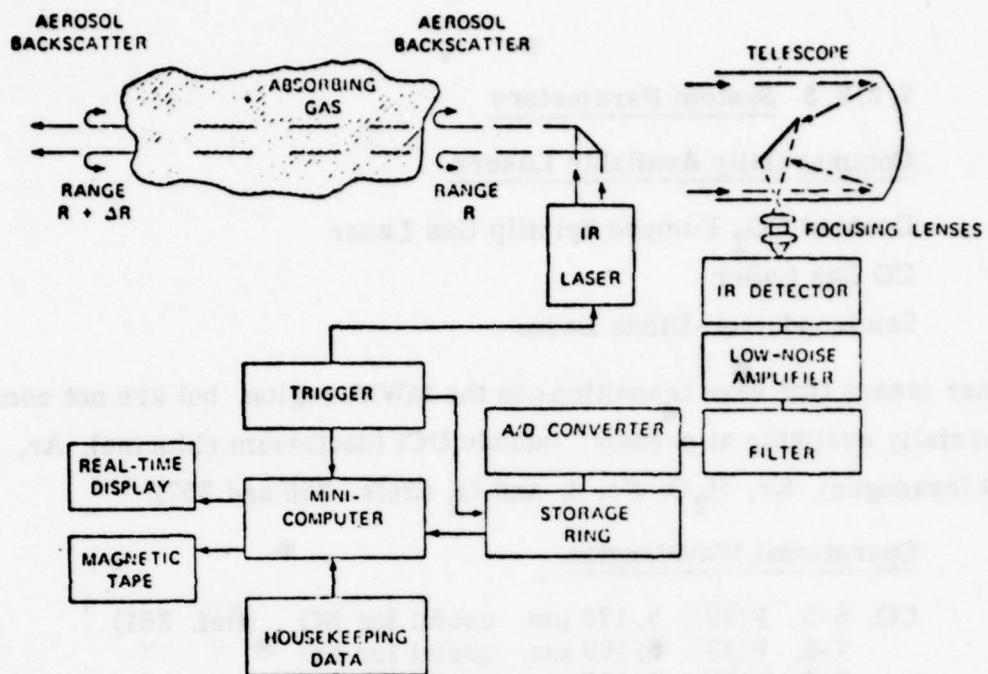


Figure 7.2.2-1. Block Diagram for MWIR DAS System Using Single Laser and Direct Detection (adopted from Ref. 249).

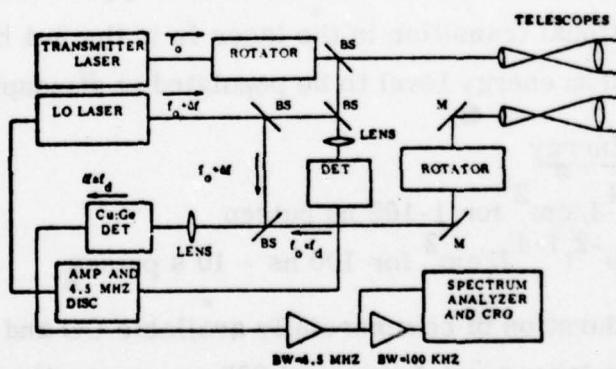


Figure 7.2.2-2. Block Diagram for MWIR DAS System Using Single Laser and Heterodyne Detection (adopted from Ref. 258).

7. 2. 2. 3 System ParametersCommercially Available Lasers

Doubled CO<sub>2</sub> Pumped Spinflip Gas Laser

CO Gas Laser

Semiconductor -Diode Laser

Other lasers that have transitions in the MWIR region, but are not commercially available at present, include DCI (deuterium chlorine), Ar, CN (cyanogen), Kr, H<sub>2</sub>O, Xe, I, and O<sub>2</sub> (Refs. 256 and 257).

Operational Wavelengths

CO, 6-5, P(20)	5. 176 $\mu\text{m}$	useful for NO	(Ref. 251)
7-6, P(13)	5. 166 $\mu\text{m}$	useful for NO	" "
7-6, P(15)	5. 187 $\mu\text{m}$	useful for NO	" "
9-8, P(9)	5. 262 $\mu\text{m}$	useful for NO	" "

The coincidence of other transitions of the available lasers to carbon monoxide and nitrous oxide have not been reported as yet. The CO gas laser cannot be used to observe CO in the atmosphere since the lowest observed vibrational transition in the laser is in the 5-4 band [P(18) and up], which is too high an energy level to be populated at atmospheric temperatures.

Laser Energy

$2 \times 10^{-4} \text{ J/cm}^2$  for 1-100 ns pulses

$1. 1 \times 10^{-2} t^{1/4} \text{ J/cm}^2$  for 100 ns - 10 s pulses

Shortest pulse duration of commercially available CO and doubled CO<sub>2</sub> pumped spin flip lasers are 1  $\mu\text{sec}$  and 200 ns, respectively. In order to obtain a resolution element of 15 m, the gating time of the receiver can be adjusted to 100 nsec.

## 7. 2. 2. 3b

### Detector

Commercially available detectors with highest  $D^*$  and shortest risetimes at operating temperatures of 77K are

Indium-Antimonide ( $D^* \sim 10^{11} \text{ cm Hz}^{1/2}/\text{W}$ ,  $t < 1\mu\text{s}$ )

Gold-doped Germanium ( $D^* \sim 2 \times 10^{10} \text{ cm Hz}^{1/2}/\text{W}$ ,  $t \sim 1\mu\text{s}$ )

Active detector areas can range from  $0.008$  to  $1 \text{ mm}^2$ .

### Optics

Collecting Aperture  $A_o$

Solid Angle  $\Omega_o$

Optical Efficiency  $\eta_o$

Detector Optics  $A_d \Omega_d (= A_o \Omega_o)$

These optical parameters are variables that must be chosen to fulfill the operational requirements (see below). For heterodyne detection, the constraint for the coherent aperture must be taken into account ( $A_o \Omega_o \approx \lambda^2$ ).

### Electronic Bandpass

$$\Delta f = \frac{1}{4t_c} = \frac{1}{4 n t_s}$$

where  $t_s$  is the pulse duration. The number of pulses to be sampled is a variable that can be used to increase the SNR.

#### 7.2.2.4 Theoretical Performance Prediction

Based upon the selected system parameters, the performance can be predicted for a detector-noise-limited system. The signal-to-noise ratio for the determination of the pollutant concentration by DAS is given by

$$\text{SNR} = \frac{\ln Q^1}{dP \sqrt{(1/P_1)^2 + (1/P'_1)^2 + (1/P_2)^2 + (1/P'_2)^2}}$$

where

$$\ln Q^1 = \ln \frac{P_1 P'_2}{P'_1 P_2}$$

$$P_1 = (G/R^2) e^{-2k_1 C R}$$

$$P'_1 = (G/(R + \Delta R)^2) e^{-2k_1 C (R + \Delta R)}$$

$$P_2 = (G/R^2) e^{-2k_2 C R}$$

$$P'_2 = (G/(R + \Delta R)^2) e^{-2k_2 C (R + \Delta R)}$$

$$G = \eta P_t \Delta R N(R) \beta A_o$$

$$dP = \text{NEP}/F = (A_d \Delta f)^{1/2} (D^*)^{-1}/F = \left( \frac{A_d}{4n t_s} \right)^{1/2} (D^*)^{-1}/F$$

$$F = \eta Q \lambda^3 / 2 \Omega_d \sqrt{A_d B} hc D^*$$

The SNR may be simplified, i.e.,

$$\text{SNR} = \frac{Q P_{\text{eff}}}{2 \text{NEP}/F}$$

where

$$Q = 2(k_1 C_1 - k_2 C_2) \Delta R$$

$$P_{\text{eff}} = G \xi(R)$$

$$\xi(R) = R^{-2} e^{-2kCR}$$

In the following a stepwise description for the calculation of SNR is given

Step 1: Calculate:  $\text{NEP}/F$

$$\text{Assume: } D^* = 10^{11} \text{ cm Hz}^{1/2} \text{ W}^{-1}$$

$$F = 10 \text{ for heterodyne detection}$$

$$t_s = 100 \text{ nsec}$$

**Result:** Plot in Figure 7. 2. 2-3 shows  $\text{NEP}/F$  versus  $A_d$  for different number of pulses  $n$ .

Step 2: Calculate:  $G$

$$\text{Assume: } N(R)\beta \approx 8 \times 10^{-8} \text{ cm}^{-1} \text{ ster}^{-1}$$

$$\Delta R = 1500 \text{ cm}$$

$P_t = 2 \times 10^4 \text{ W}$  for a  $2 \times 10^{-3} \text{ J}$  laser, having a  $10 \text{ cm}^2$  beam area and a pulse duration of 100 nsec

**Result:** Plot in Figure 7. 2. 2-4 shows  $G$  versus receiver aperture area  $A_o$  for three values of overall efficiency (optical and mechanical shutters)

Step 3: Calculate:  $\xi(R) = R^{-2} e^{-2kCR}$

$$\text{Assume: } kC = 0, .3, 1, 3 \text{ km}^{-1}$$

**Result:** Plot in Figure 7. 2. 2-5 shows  $\xi(R)$  versus  $R$  for the above values of  $kC$

Step 4: Calculate:  $P_{\text{eff}} = G \xi(R)$

**Assume:** Useful range of  $R$  between 100 and 1000 m

**Result:** Plot in Figure 7. 2. 2-6 which shows  $P_{\text{eff}}$  vs.  $\xi(R)$  for different values of  $G$ .

7.2.2.4c

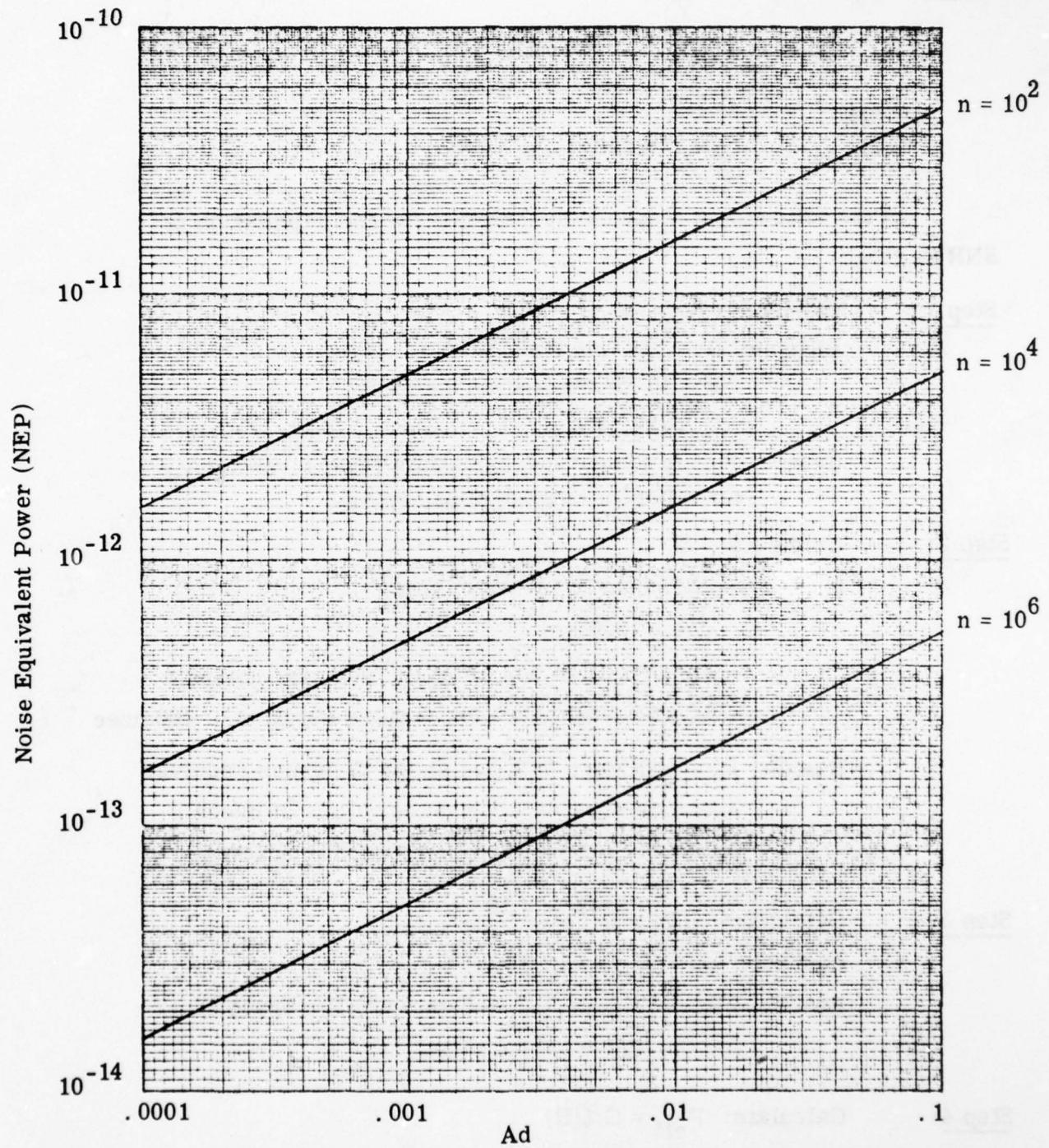


Figure 7.2.2-3. NEP versus  $A_d$  for Different Values of Number of Pulses, Assuming  $D^* = 10^{11} \text{ cm H}^{1/2} \text{ W}^{-1}$  and  $t_s = 100 \text{ ns}$ .

7. 2. 2. 4d

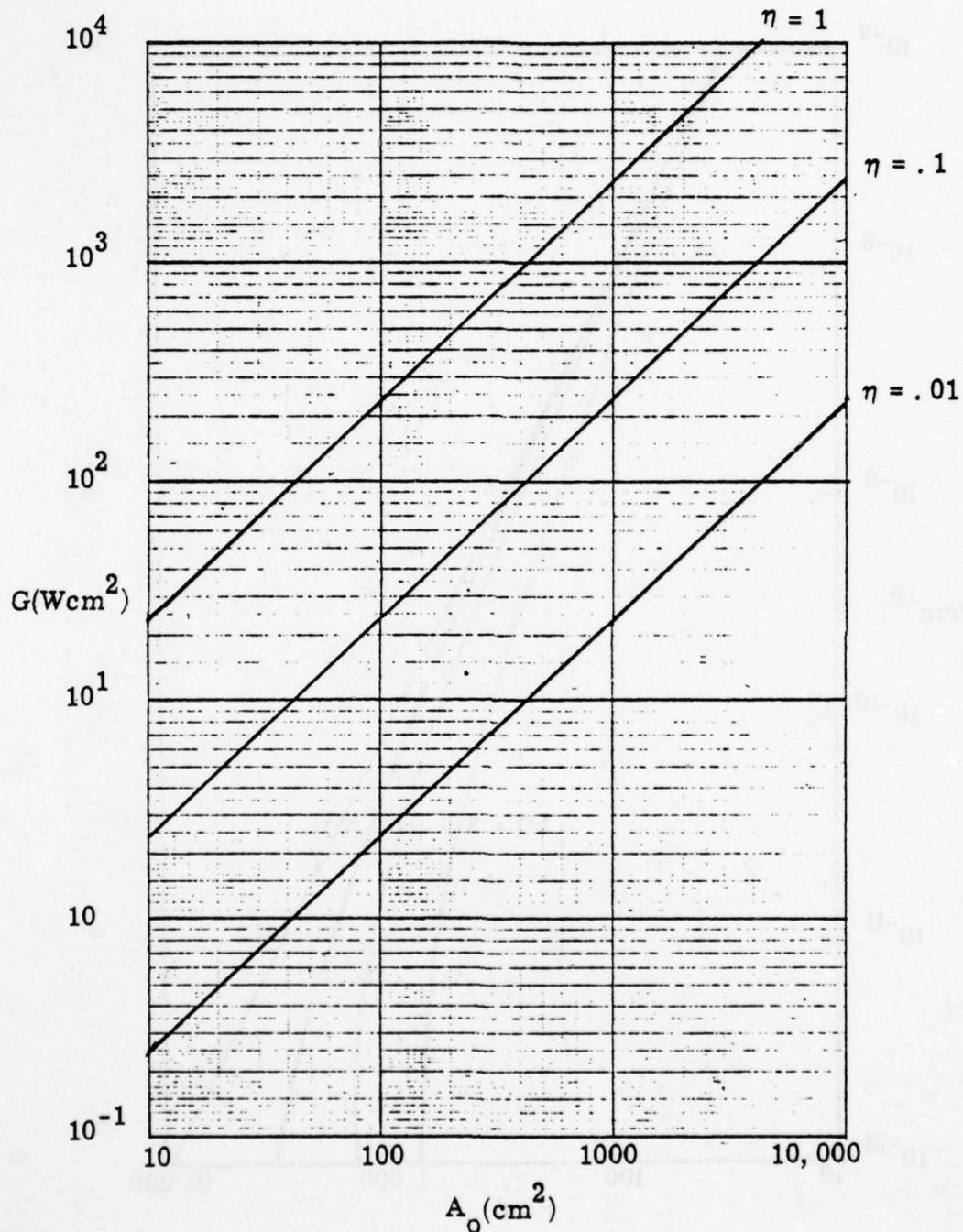


Figure 7. 2. 2-4. Function  $G$  versus  $A_0$  for Three Values of  $\eta$ , using  $\Delta R = 15$  m,  $N(\bar{R})\beta = 8 \times 10^{-8}$  cm<sup>-1</sup>ster<sup>-1</sup> and  $P_t = 2 \times 10^{-3}$  J for 10 cm<sup>2</sup> laser beam area.

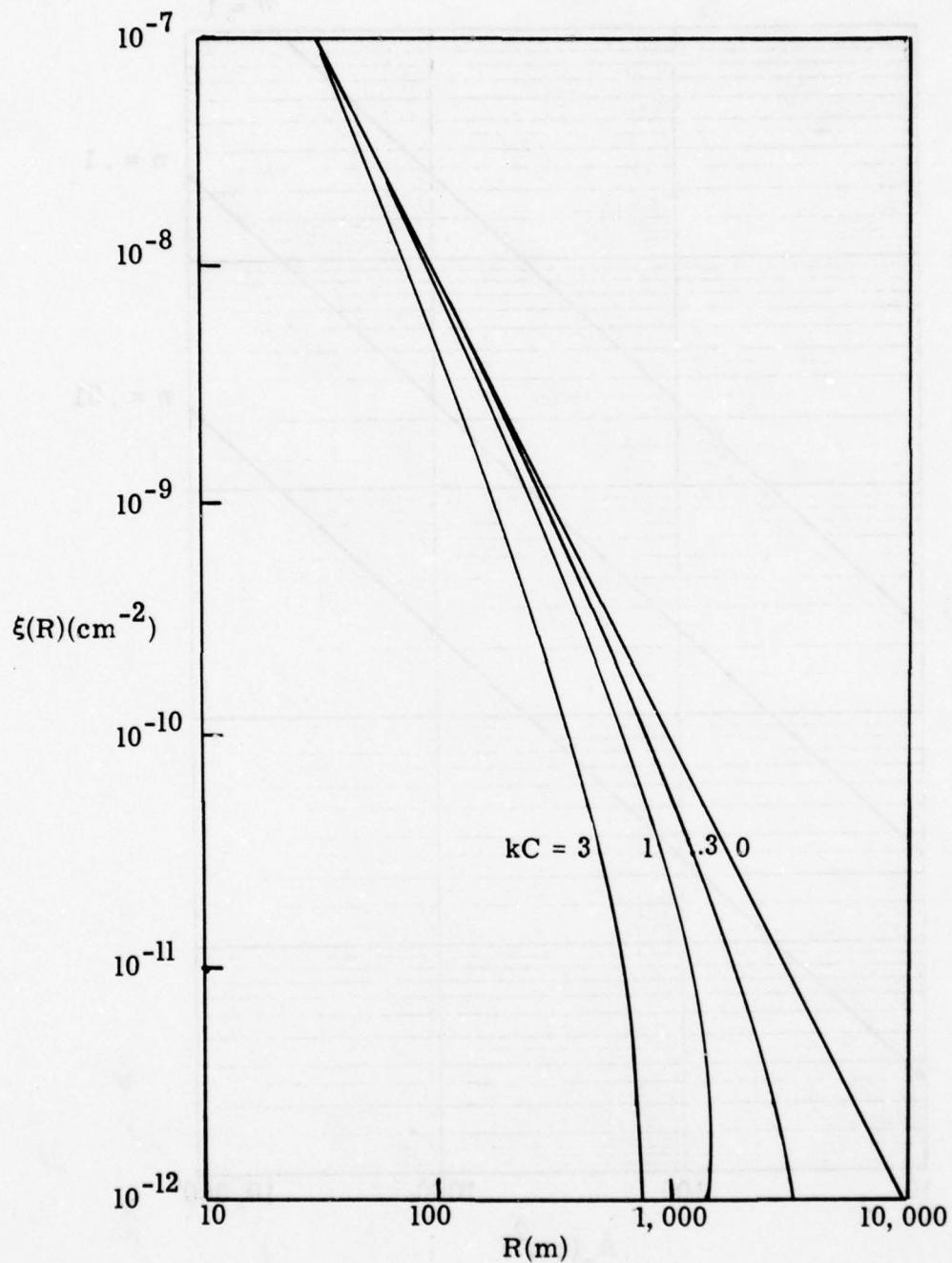


Figure 7.2.2-5. Function  $\xi(R)$  vs. Range for Different Values of  $kC$  (km<sup>-1</sup>)

7. 2. 2. 4f

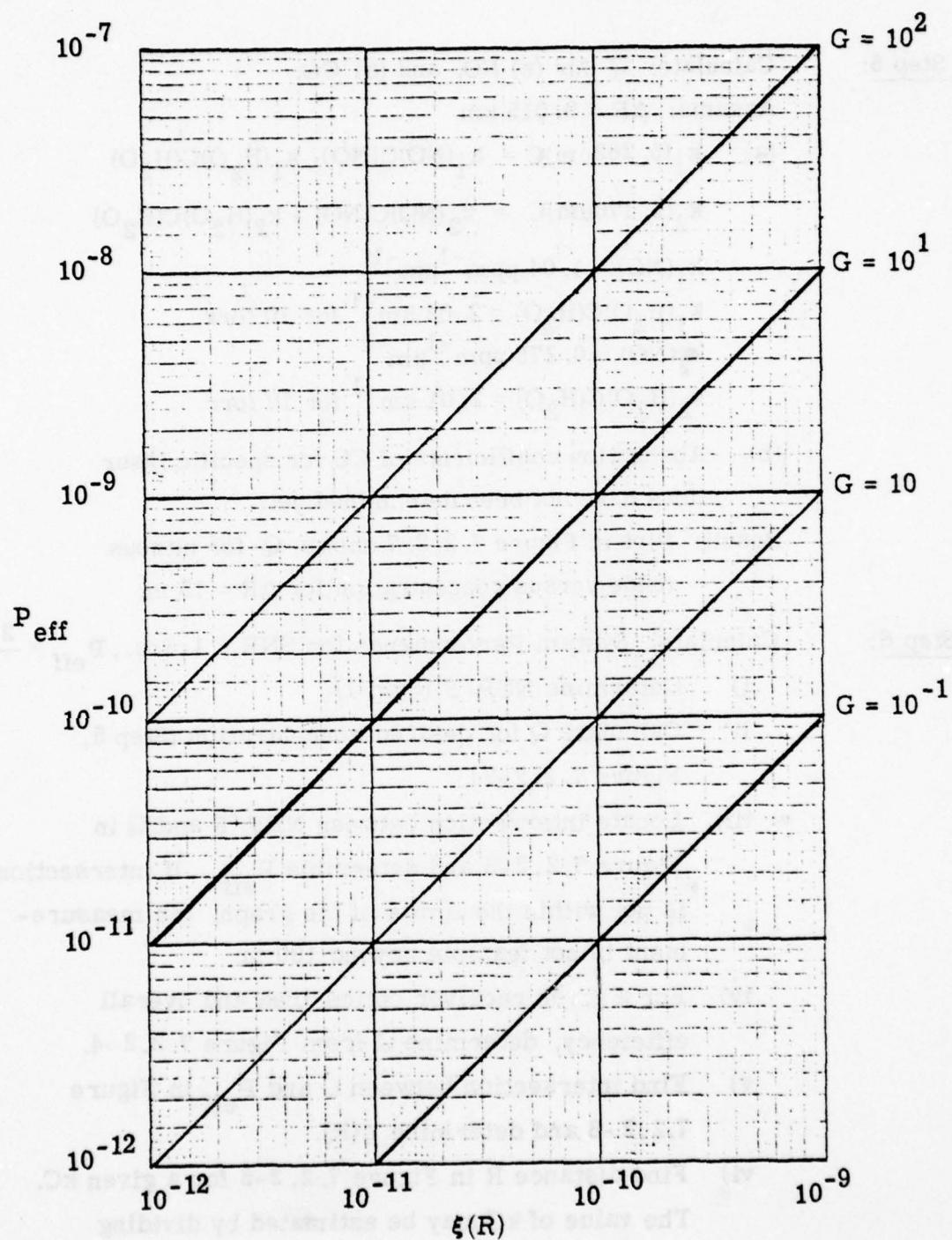


Figure 7.2.2-6.  $P_{\text{eff}}$  vs. the Function  $\xi(R)$  for Different Values of  $G$

Step 5: Calculate:  $Q$  for (a) NO, and (b) CO.

Assume:  $\Delta R = 0.015 \text{ km}$

$$(a) k_1(5.262\mu\text{m})C = k_1(\text{NO})C(\text{NO}) + k_1(\text{H}_2\text{O})C(\text{H}_2\text{O})$$

$$k_2(5.176\mu\text{m})C = k_2(\text{NO})C(\text{NO}) + k_2(\text{H}_2\text{O})C(\text{H}_2\text{O})$$

$$k_1(\text{NO}) = 1.04 \text{ ppm}^{-1}\text{km}^{-1}$$

$$k_1(\text{H}_2\text{O})C(\text{H}_2\text{O}) = 2.02 \text{ km}^{-1} \text{ for } 10 \text{ torr}$$

$$k_2(\text{NO}) = 0.275 \text{ ppm}^{-1}\text{km}^{-1}$$

$$k_2(\text{H}_2\text{O})C(\text{H}_2\text{O}) = 2.01 \text{ km}^{-1} \text{ for } 10 \text{ torr}$$

(b) Absorption coefficients of CO for specific laser lines have not been determined yet.

Result: Plot in Figure 7.2.2.7 shows  $Q$  for nitrous oxide versus concentration for  $\Delta R = 15 \text{ m}$ .

Step 6: Calculate: System Performance for  $\text{SNR} = 1$ , i. e.,  $P_{\text{eff}} = \frac{2 \text{ NEP/F}}{Q}$

i) Determine  $\text{NEP/F}$  (Step 1)

ii) Calculate  $Q$  for desired concentration (Step 5, Figure 7.2.2-7)

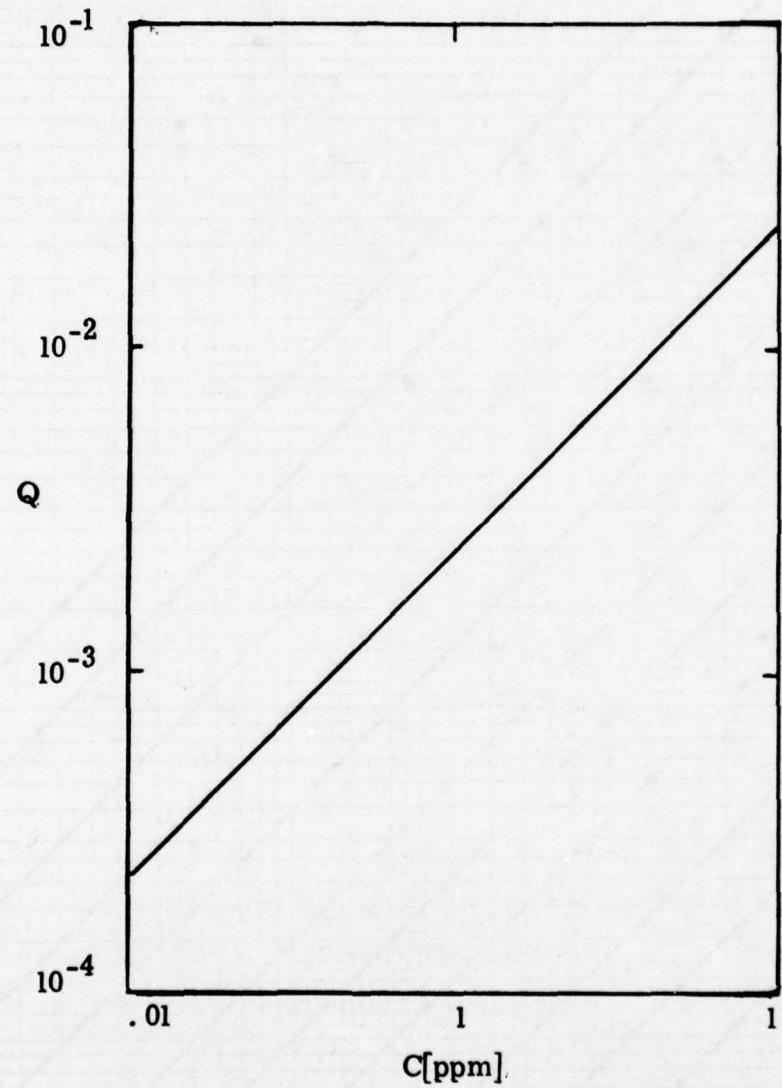
iii) Locate intersection between  $\text{NEP/F}$  and  $Q$  in Figure 7.2.2-8 and determine  $P_{\text{eff}}$ . If intersection is not within the limits of the graph, the measurement is not feasible beyond 100 m.

iv) For a given receiver optics area and overall efficiency, determine  $G$  from Figure 7.2.2-4.

v) Find intersection between  $G$  and  $P_{\text{eff}}$  in Figure 7.2.2-6 and determine  $\xi(R)$ .

vi) Find distance  $R$  in Figure 7.2.2-5 for a given  $kC$ . The value of  $kC$  may be estimated by dividing 0.015 into  $Q$ , because  $Q \approx kC\Delta R$  and  $\Delta R = 0.015 \text{ km}$ .

7. 2. 2. 4h



**Figure 7. 2. 2-7.**  $Q$  versus Concentration of NO for a Resolution Element of 15 m.

7. 2. 2. 4i

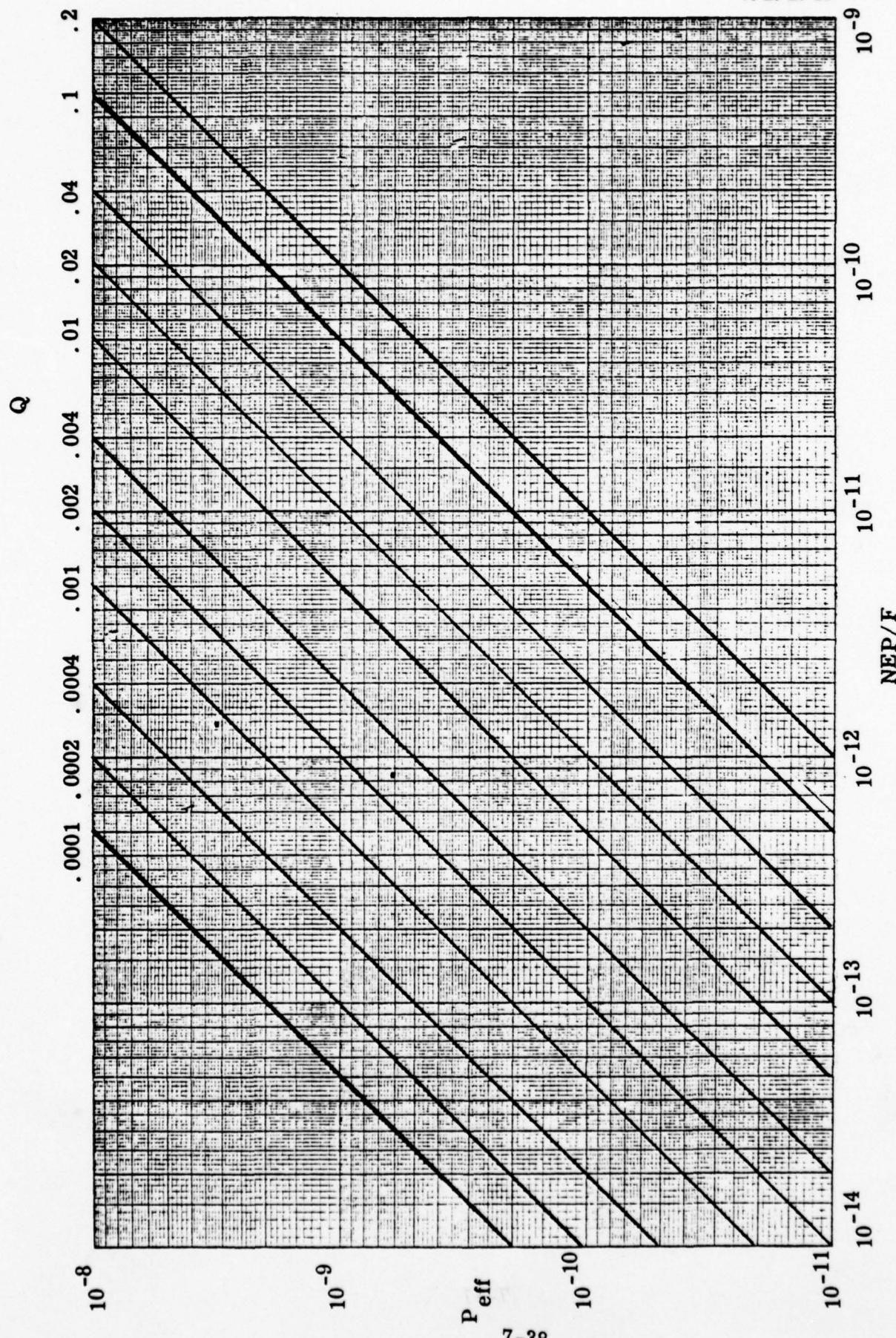


Figure 7.2.2-8.  $P_{\text{eff}}$  versus NEP/F for Different Values of  $Q$ .

#### 7.2.2.5 Special Performance Requirements

The general requirements applicable to all remote monitors were described in Section 7.1.1. For  $\text{NO}_x$ , the range of interest is from 0 to .35 ppm. This overall range may be divided into three subranges:

Low	0.02 to 0.08 ppm
Medium	0.10 to 0.20 ppm
High	0.25 to 0.35 ppm

However, the concentrations for NO are expected to be less than those of  $\text{NO}_x$ . The MWIR-DAS remote monitor must measure the  $\text{NO}_x$  concentration as determined by a reference method for the three ranges to within

Low	0.02 ppm
Medium	0.02 ppm
High	0.03 ppm

For carbon monoxide, the range for automated methods must be 45 ppm with the following ranges

Low	7-11 ppm
Medium	20-30 ppm
High	35-45 ppm

#### 7.2.2.6 Data Analysis Procedure

The concentration (in ppm) is determined in a very good approximation by

$$C(\text{ppm}) = \frac{10^6 \ln Q}{2 (k_1 - k_2) \Delta R}$$

7. 2. 2. 6b

where

$$Q = \frac{P_1(R) P_2(R + \Delta R)}{P_1(R + \Delta R) P_2(R)}$$

Fig. 7. 2. 2-9 is a typical received signal from the on-wavelength (lower curve) and off-wavelength (upper curve) laser beams as a function of range. The four signals are determined from analog signals as given in Figure 7. 2. 2-9. The absorption coefficients  $k_1$  and  $k_2$  are as follows:

	NO	CO
$k_1(\text{ppmkm})^{-1}$	1. 04 @ 5. 262 $\mu\text{m}$	Absorption coefficients of CO for these laser lines are not yet known.
$k_2(\text{ppmkm})^{-2}$	0. 275 @ 5. 176 $\mu\text{m}$	

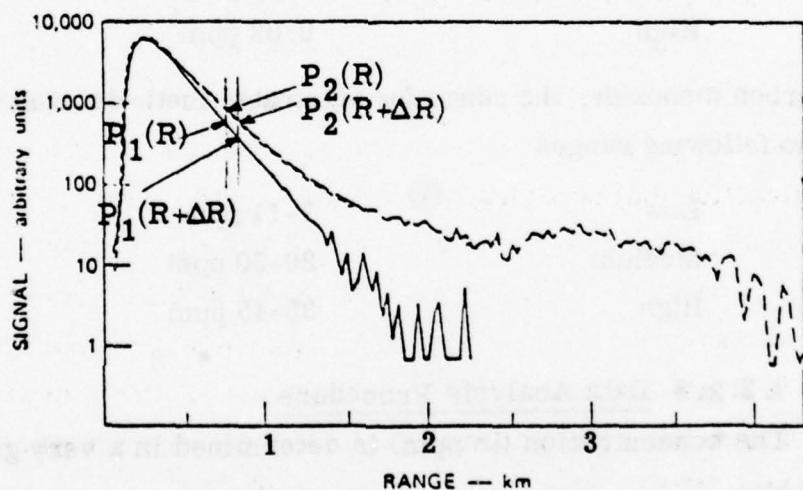


Figure 7. 2. 2-9. Analog Signals  $P_1(R)$ ,  $P_2(R)$ ,  $P_1(R + \Delta R)$  and  $P_2(R + \Delta R)$

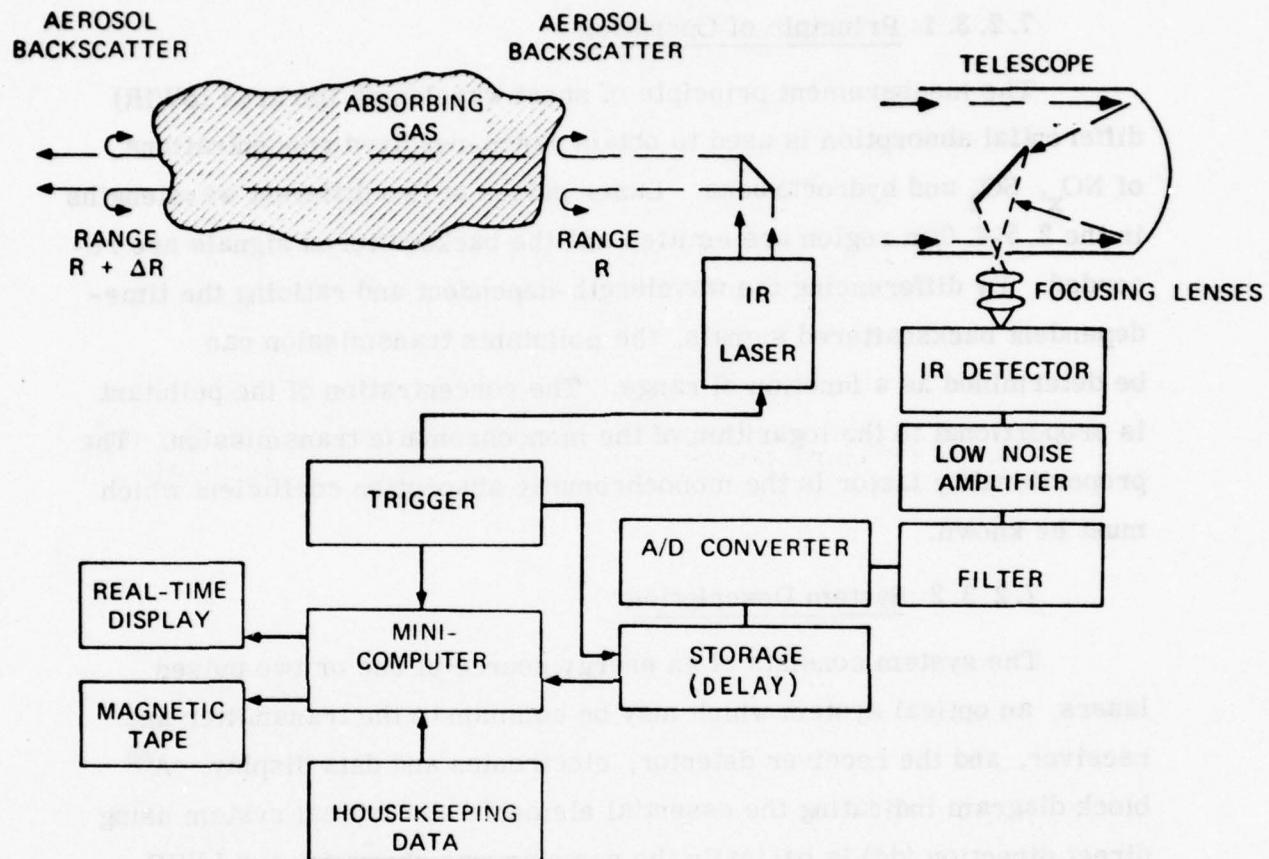
### 7. 2. 3 SWIR Differential Absorption

#### 7. 2. 3. 1 Principle of Operation

The measurement principle of short wavelength infrared (SWIR) differential absorption is used to obtain range-resolved concentrations of  $\text{NO}_x$ ,  $\text{SO}_2$  and hydrocarbons. Laser pulses at two different wavelengths in the 2.5-4.0  $\mu\text{m}$  region are emitted and the backscattered signals are recorded. By differencing the wavelength-dependent and ratioing the time-dependent backscattered signals, the pollutants transmission can be determined as a function of range. The concentration of the pollutant is proportional to the logarithm of the monochromatic transmission. The proportionality factor is the monochromatic absorption coefficient which must be known.

#### 7. 2. 3. 2 System Description

The system consists of an energy source of one or two pulsed lasers, an optical system which may be common to the transmitter and receiver, and the receiver detector, electronics and data display. A block diagram indicating the essential elements of a typical system using direct direction (dd) is basically the same as was shown for the LWIR system in Figure 7. 2. 3-1. Heterodyne detection (hd) is not useful for SWIR. It should be noted that no prototype SWIR-DAS system, using two lasers has been tested as yet. The maximum permissible energy (MPE) for laser systems has been promulgated by DHEW in 21CFR1040. If the regulations of the American National Standards Institute (ANSI) are adopted, the MPE may be increased by a factor 50.



**Figure 7. 2. 3-1.** Block Diagram for SWIR DAS System Using Single Laser and Direct Detection (adopted from Ref. 249).

7. 2. 3. 3 System ParametersCommercially Available Lasers

HF Gas Laser

DF Gas Laser

Other lasers that have transitions in the SWIR region, but are not commercially available at present, include Kr, Ne, Ar, I, Xe, Br, O<sub>2</sub>, Cl, Cs, N<sub>2</sub>, C, HCl and HBr (Refs. 256 and 257).

Operational Wavelengths

Have not been determined yet. These wavelengths will determine which of the above lasers are actually usable for this technique.

Laser Energy

$2 \times 10^{-4} \text{ J/cm}^2$  for 1-100 ns pulses

$1.1 \times 10^{-2} t^{1/4} \text{ J/cm}^2$  for 100 ns - 10 s pulses

Shortest pulse duration of commercially available HF and DF lasers is 500 nsec and 300 nsec, respectively. In order to obtain a resolution element of 15 m, this will need to be reduced to 100 nsec. However, there are no sensitive detectors available with such short rise times. Available energy exceeds MPE by orders of magnitude. ANSI regulations would permit 50 fold increase in labor energy.

Detector

Commercially available detectors with highest D\* and shortest risetimes at operating temperatures of 200K are

Lead-Sulfide ( $D^* \sim 2 \times 10^9 \text{ cm Hz}^{1/2}/W$ ,  $t_c \sim 3 \mu\text{sec}$ ,  $\lambda_{\max} = 3.5 \mu\text{m}$ )  
( $D^* \sim 2.5 \times 10^9 \text{ cm Hz}^{1/2}/W$ ,  $t_c \sim 1 \mu\text{sec}$ ,  $\lambda_{\max} = 4 \mu\text{m}$ )

7.2.3.3b  
7.2.3.4a

Active areas can range from 0.001 to 8 mm<sup>2</sup> for the detector peaking at 3.5 μm, but range from 1 to 16 mm<sup>2</sup> for the detector peaking at 4 μm. The long rise time of 1000 nsec may cause a severe loss of sensitivity as the detector cannot respond significantly to the laser pulse.

### Optics

Collecting Aperture	A <sub>o</sub>
Solid Angle	Ω <sub>o</sub>
Optical Efficiency	η <sub>opt</sub>
Detector Optics	A <sub>d</sub> Ω <sub>d</sub> (=A <sub>o</sub> Ω <sub>o</sub> )

These optical parameters are variables that must be chosen to fulfill the operational requirements (see below).

### Electronic Bandpass

$$\Delta f = \frac{1}{4t_c} = \frac{1}{4nt_s}$$

where t<sub>s</sub> is the pulse duration. The number of pulses to be sampled is a variable that can be used to increase the SNR.

### 7.2.3.4 Theoretical Performance Prediction

Based upon the selected system parameters, the performance can be predicted for a detector-noise-limited system. The signal-to-noise ratio for the determination of the pollutant concentration by DAS is given by

$$SNR = \frac{\ln Q^1}{dP \sqrt{(1/P_1)^2 + (1/P'_1)^2 + (1/P_2)^2 + (1/P'_2)^2}}$$

where

$$\ln Q^1 =$$

$$\ln \frac{P_1 P'_2}{P'_1 P_2}$$

$$P_1 =$$

$$(G/R^2)e^{-2k_1 C R}$$

$$P'_1 =$$

$$(G/(R + \Delta R)^2)e^{-2k_1 C (R + \Delta R)}$$

$$P_2 =$$

$$(G/R^2)e^{-2k_2 C R}$$

$$P'_2 =$$

$$(G/(R + \Delta R)^2)e^{-2k_2 C (R + \Delta R)}$$

$$G =$$

$$\eta P_t \Delta R N(R) \beta A_o$$

$$dP =$$

$$NEP/F = (A_d \Delta f)^{1/2} (D^*)^{-1}/F = \left( \frac{A_d}{4 \pi t_s} \right)^{1/2} (D^*)^{-1}/F$$

$$F =$$

$$1$$

The SNR may be simplified, i. e.,

$$SNR = \frac{Q P_{eff}}{2 NEP/F}$$

where

$$Q = 2(k_1 C_1 - k_2 C_2) \Delta R$$

$$P_{eff} = G \xi(R)$$

$$\xi(R) = R^{-2} e^{-2kCR}$$

In the following a stepwise description for the calculation of SNR is given

Step 1: Calculate:  $\text{NEP}/F$

Assume:  $D^* = 3 \times 10^9 \text{ cm Hz}^{1/2} \text{W}^{-1}$

$$F = 1$$

$$t_s = 1000 \text{ nsec}$$

Result: Plot in Figure 7.2.3-2 shows  $\text{NEP}/F$  versus  $A_d$  for different number of pulses  $n$ . It should be noted that the values for  $\text{NEP}/F$  are down by 3 orders of magnitude when compared with the LWIR region.

Step 2: Calculate:  $G$

Assume:  $N(R)\beta \approx 8 \times 10^{-8} \text{ cm}^{-1} \text{ster}^{-1}$

$$\Delta R = 1500 \text{ cm}$$

$P_t = 2 \times 10^4 \text{ W}$  for a  $2 \times 10^{-3} \text{ J}$  laser, having a  $10 \text{ cm}^2$  beam area and a pulse duration of 100 nsec

Result: Plot in Figure 7.2.3-3 shows  $G$  versus receiver aperture area  $A_o$  for three values of overall efficiency (optical and mechanical shutters)

Step 3: Calculate:  $\xi(R) = R^{-2} e^{-2kCR}$

Assume:  $kC = 0, .3, 1, 3 \text{ km}^{-1}$

Result: Plot in Figure 7.2.3-4 shows  $\xi(R)$  versus  $R$  for the above values of  $kC$

Step 4: Calculate:  $P_{\text{eff}} = G \xi(R)$

Assume: Useful range of  $R$  between 100 and 1000 m

Result: Plot in Figure 7.2.3-5 which shows  $P_{\text{eff}}$  vs.  $\xi(R)$  for different values of  $G$ .

7. 2. 3. 4d

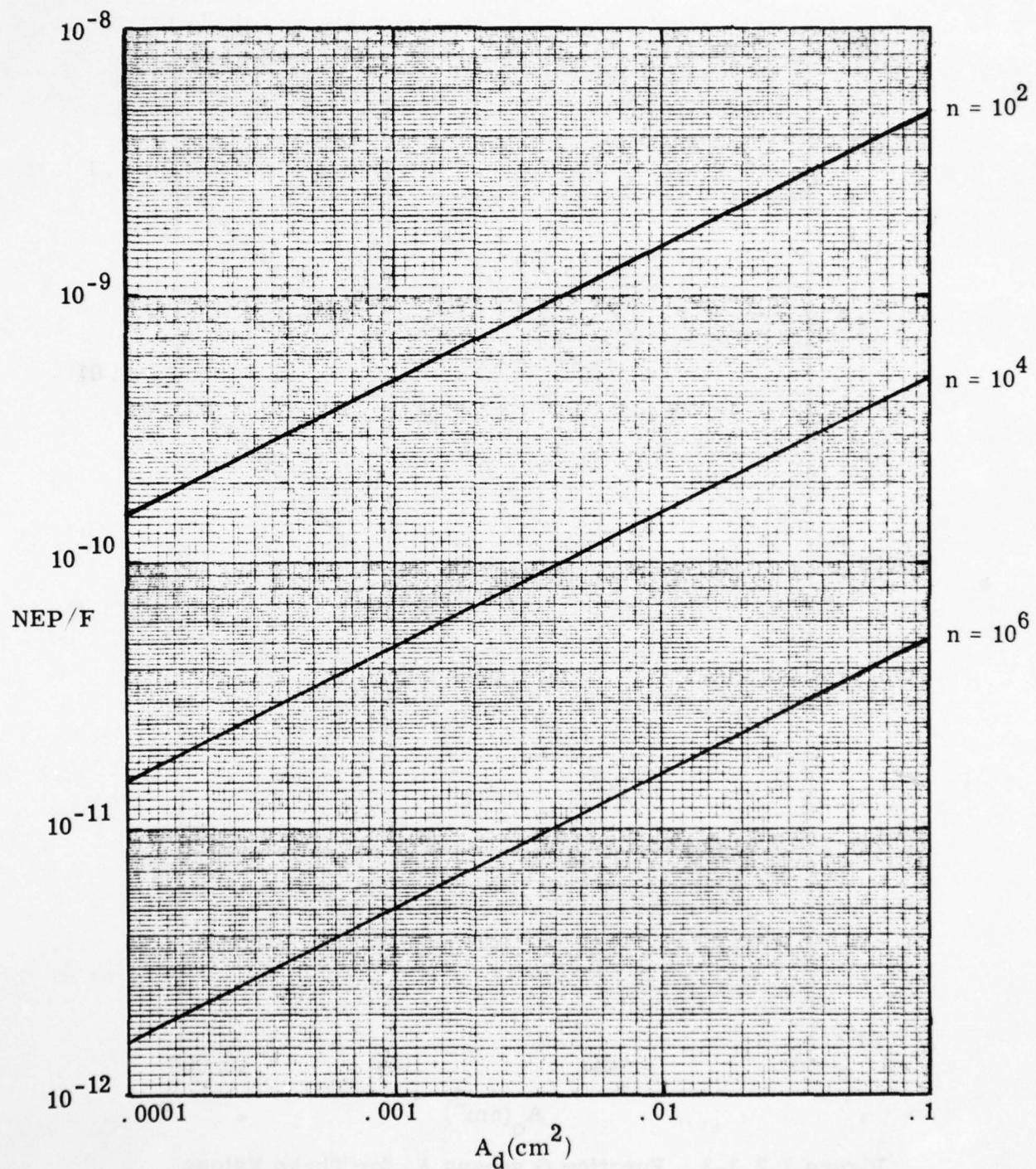


Figure 7. 2. 3-2. NEP versus  $A_d$  for Different Values of Number of Pulses, Assuming  $D^* = 3 \times 10^9 \text{ cmH}^{1/2}\text{W}^{-1}$  and  $t_s = 1000 \text{ ns}$ .

7.2.3.4e

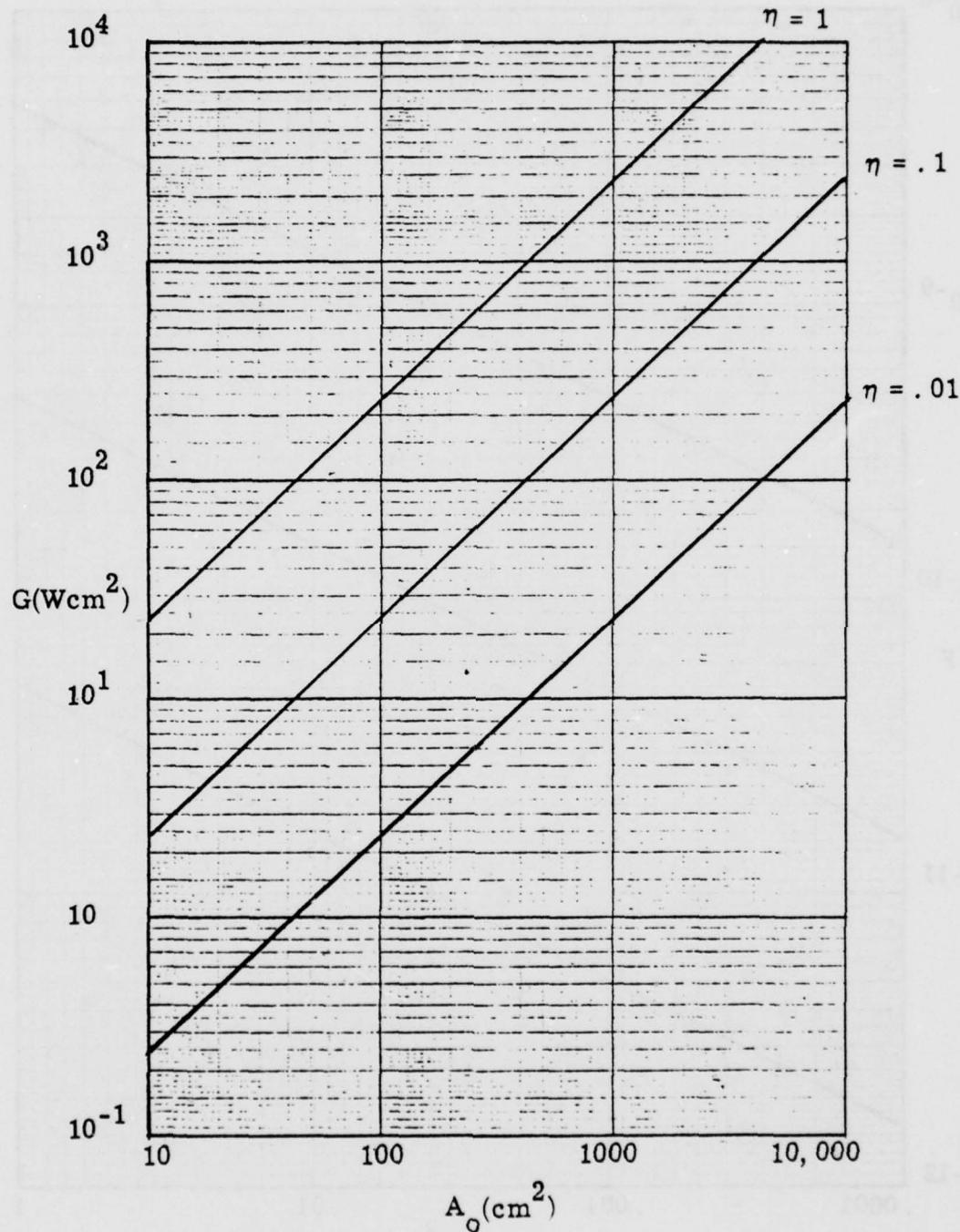


Figure 7.2.3-3. Function  $G$  versus  $A_0$  for Three Values of  $\eta$ , using  $\Delta R = 15 \text{ m}$ ,  $N(R)\beta = 8 \times 10^{-8} \text{ cm}^{-1}\text{ster}^{-1}$  and  $P_t = 2 \times 10^{-3} \text{ J}$  for  $10 \text{ cm}^2$  laser beam area.

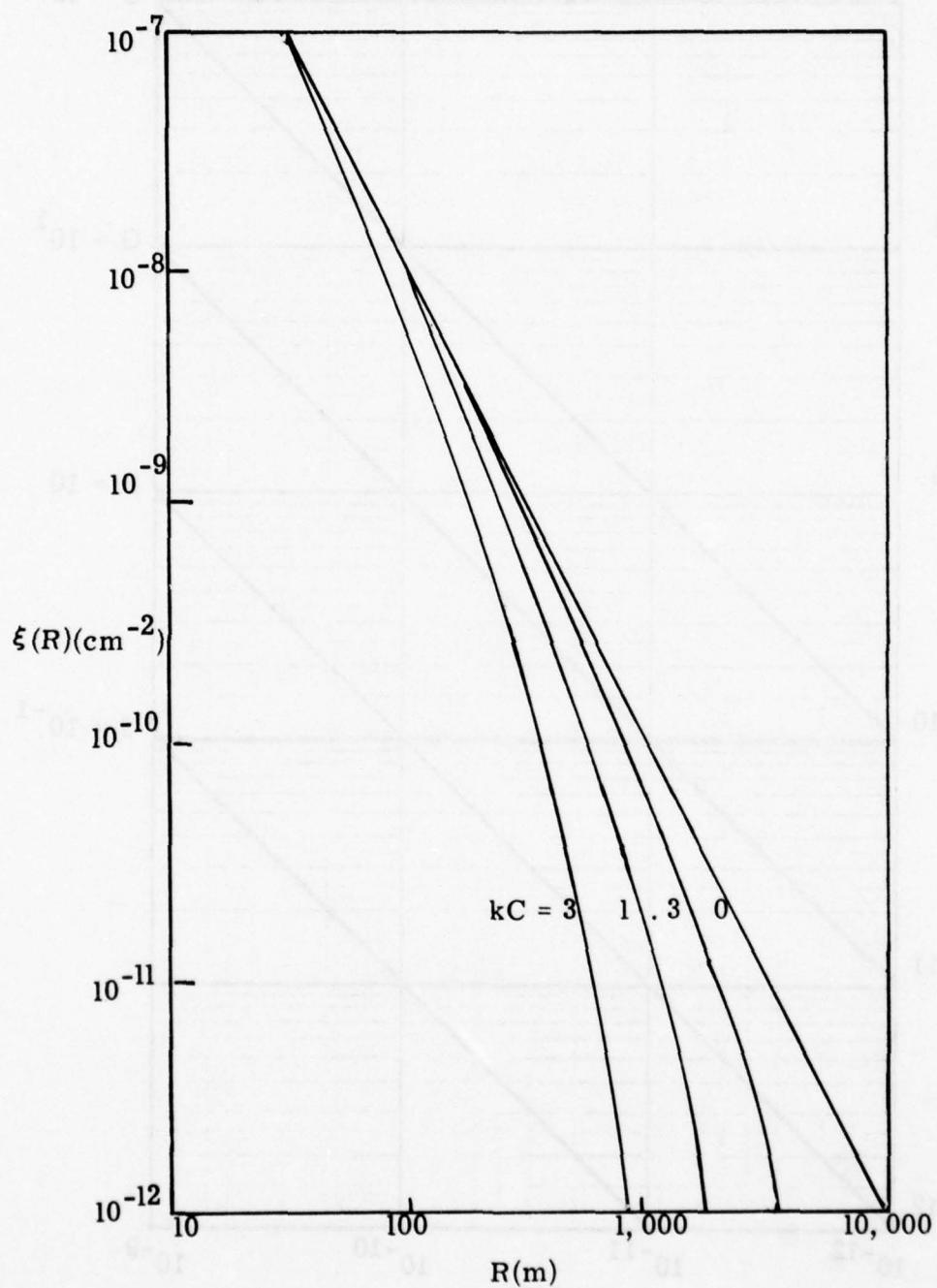


Figure 7. 2. 3-4. Function  $\xi(R)$  vs. Range for Difference Values of  $kC(\text{km}^{-1})$

7.2.3.4g

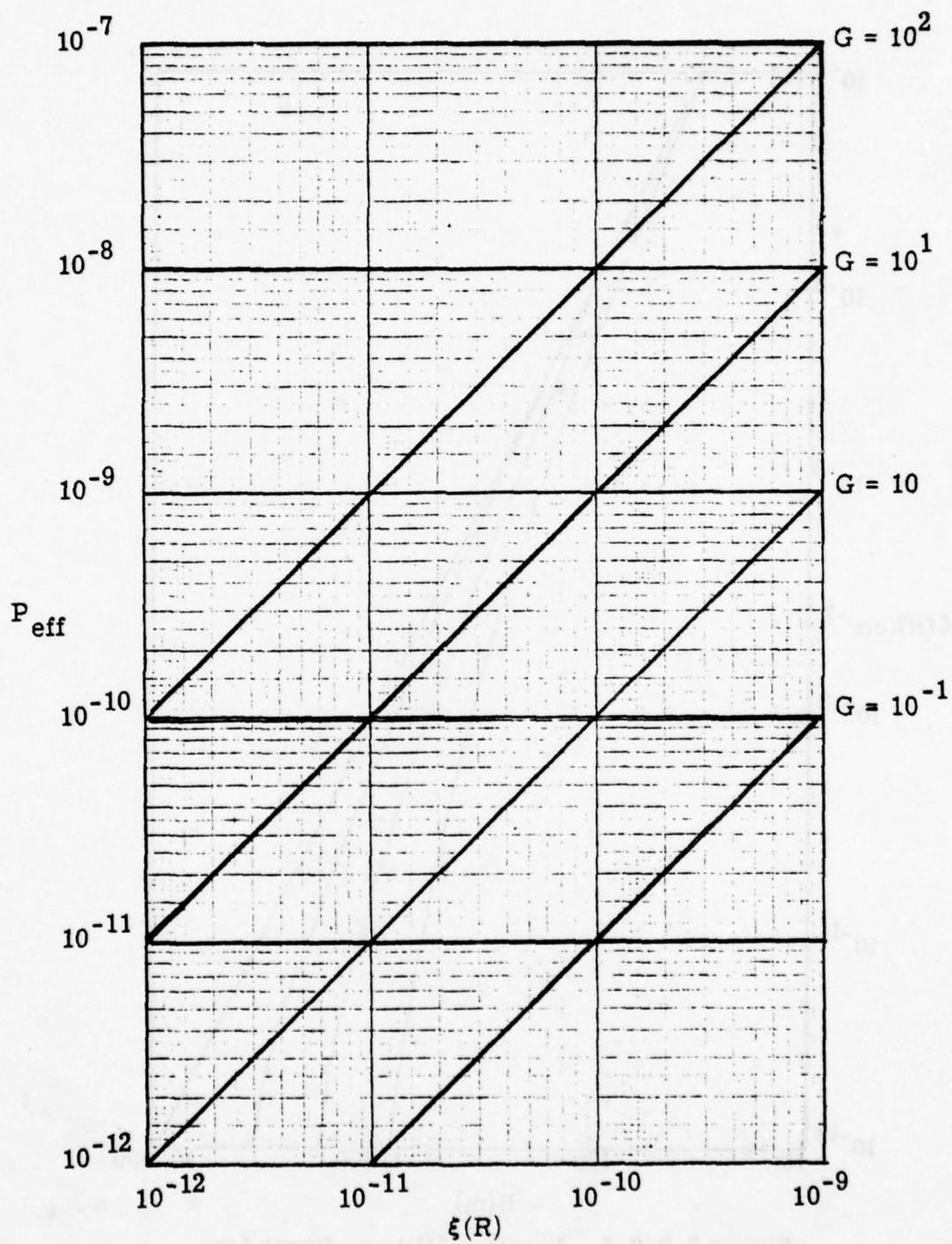


Figure 7.2.3-5.  $P_{\text{eff}}$  vs. the Function  $\xi(R)$  for Different Values of  $G$

### 7.2.3.4h

Step 5: Calculate: Q for (a)  $\text{NO}_x$ , and (b)  $\text{SO}_2$  and (c) hydrocarbons

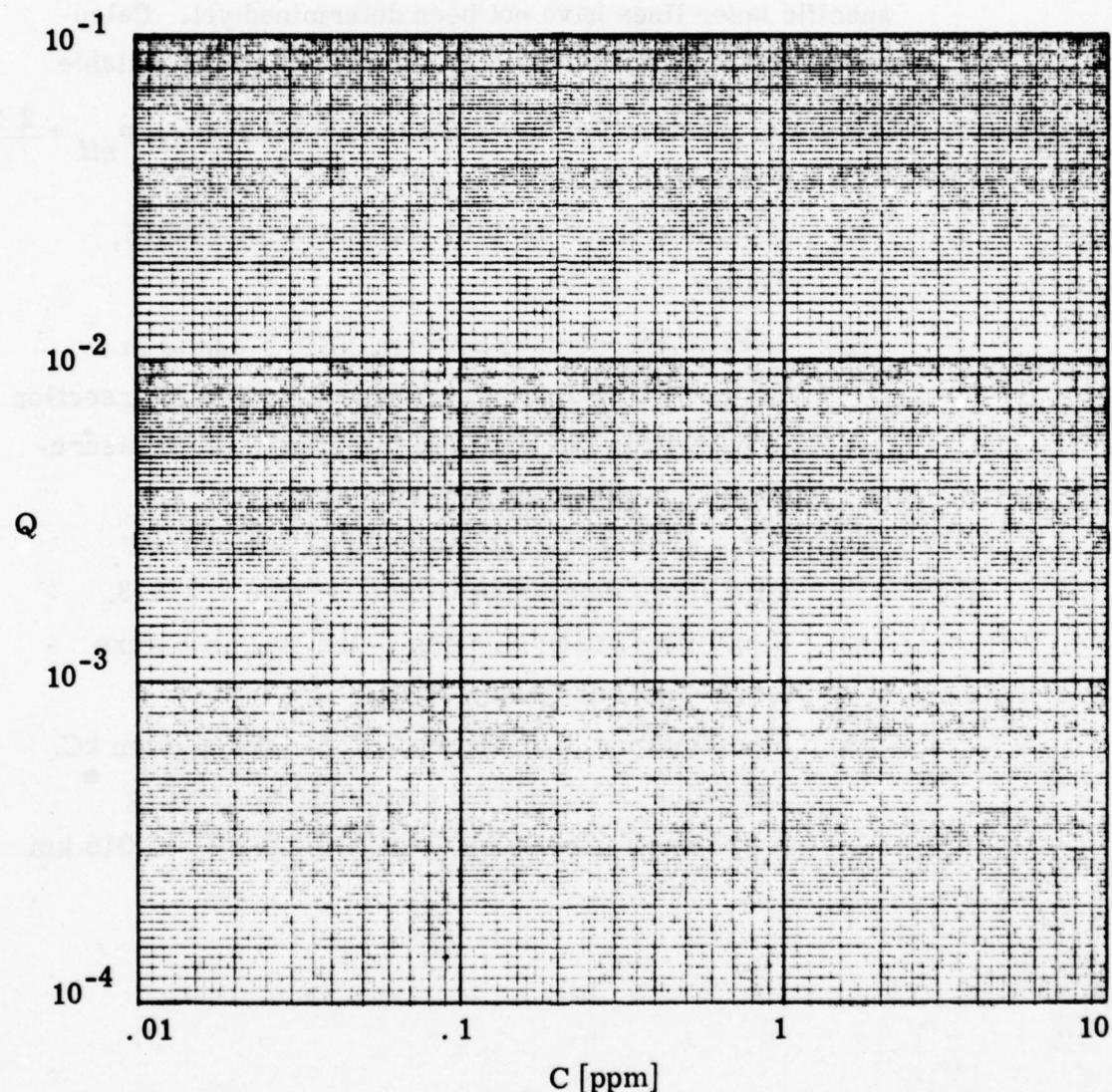
Assume:  $\Delta R = 0.015 \text{ km}$

Absorption coefficients of  $\text{NO}_x$ ,  $\text{SO}_2$  and hydrocarbons for specific laser lines have not been determined yet. Calculation cannot be completed until these values are available.

Step 6: Calculate: System Performance for  $\text{SNR} = 1$ , i. e.,  $P_{\text{eff}} = \frac{2 \text{ NEP/F}}{Q}$

- i) Determine NEP/F (Step 1)
- ii) Calculate Q for desired concentration (Step 5, Figure 7.2.3-6)
- iii) Locate intersection between NEP/F and Q in Figure 7.2.3-7 and determine  $P_{\text{eff}}$ . If intersection is not within the limits of the graph, the measurement is not feasible beyond 100 m.
- iv) For a given receiver optics area and overall efficiency, determine G from Figure 7.2.3-3.
- v) Find intersection between G and  $P_{\text{eff}}$  in Figure 7.2.3-6 and determine  $\xi(R)$ .
- vi) Find distance R in Figure 7.2.3-4 for a given kC. The value of kC may be estimated by dividing 0.015 into Q, because  $Q \approx kC\Delta R$  and  $\Delta R = 0.015 \text{ km}$ .

7. 2. 3. 4i



**Figure 7. 2. 3-6.**  $Q$  versus Concentration of  $\text{NO}_x$ ,  $\text{SO}_2$  and  $\langle \text{HC} \rangle$  for a Resolution Element of 15 m.  
See Step 5, absorption coefficients required for this graph are not yet determined.

7. 2. 3. 4j

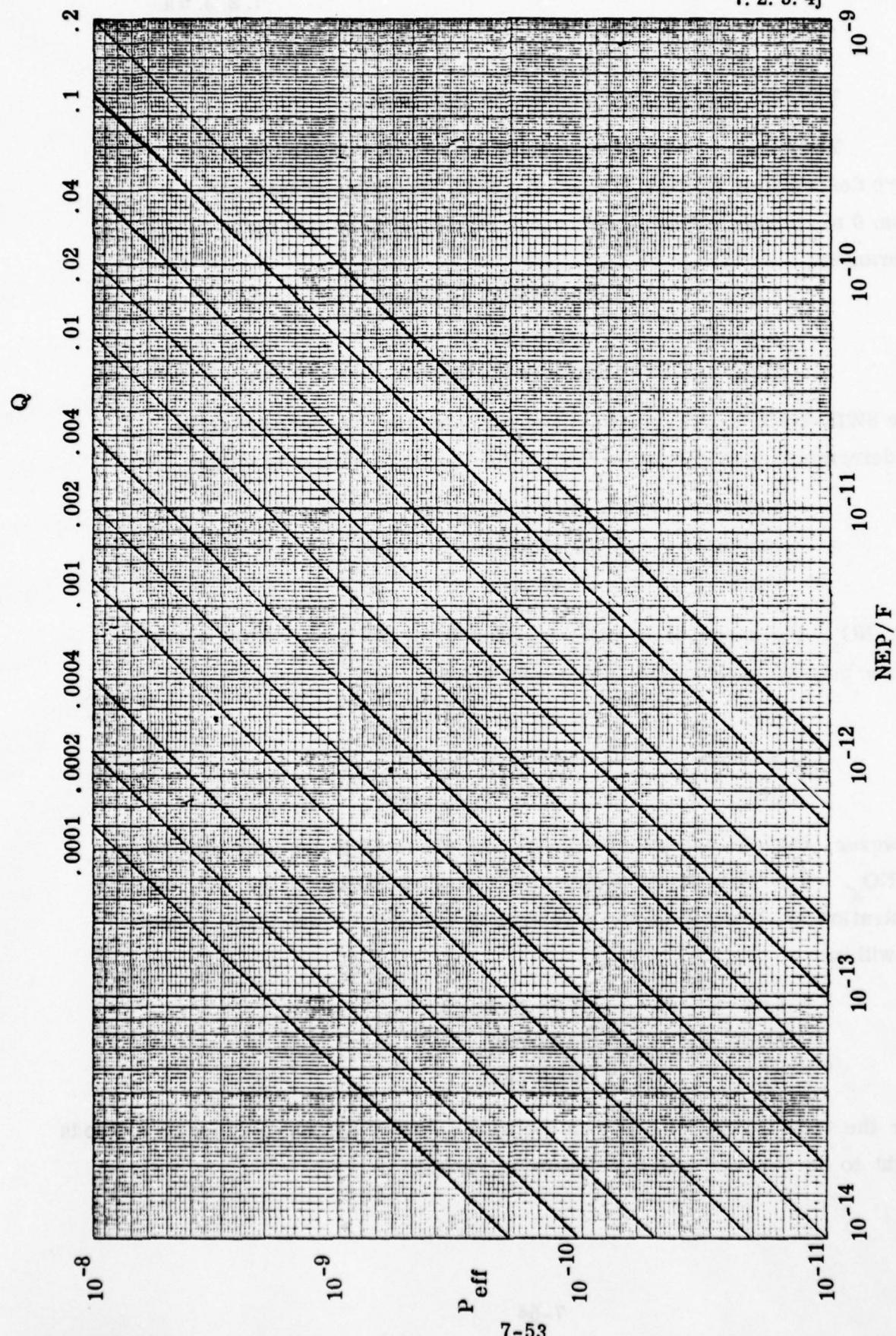


Figure 7.2.3.-7.  $P_{\text{eff}}$  versus  $\text{NEP}/F$  for Different Values of  $Q$ .

## 7.2.3.5 a

### 7.2.3.5 Special Performance Requirements

The general requirements applicable to all remote monitors were described in Section 7.1.1. For SO<sub>2</sub>, the range of interest is from 0 to .5 ppm. This overall range may be divided into three subranges:

Low	0.02 to 0.05 ppm
Medium	0.10 to 0.15 ppm
High	0.40 to 0.50 ppm

The SWIR-DAS remote monitor must measure the SO<sub>2</sub> concentration as determined by a reference method for the three ranges to within

Low	0.02 ppm
Medium	0.03 ppm
High	0.04 ppm

For NO<sub>x</sub>, the range of interest is from 0 to .35 ppm. This overall range may be divided into three subranges:

Low	0.02 to 0.08 ppm
Medium	0.10 to 0.20 ppm
High	0.25 to 0.35 ppm

However, the concentrations for NO are expected to be less than those of NO<sub>x</sub>. The SWIR-DAS remote monitor must measure the NO<sub>x</sub> concentration as determined by a reference method for the three ranges to within

Low	0.02 ppm
Medium	0.02 ppm
High	0.03 ppm

For the total hydrocarbons (non-methane), the range for automated methods ought to be 2 ppm, with the following ranges

7. 2. 3. 5b  
7. 2. 3. 6a

Low	.2 - .28 ppm
Medium	.5 - .6 ppm
High	1 - 2 ppm

In general, however, the concentration of ethylene will appreciably be less than those for the total hydrocarbons/non-methane concentrations.

#### 7. 2. 3. 6 Data Analysis Procedure

The concentration (in ppm) is determined in a very good approximation by

$$C(\text{ppm}) = \frac{10^6 \ln Q}{2 (k_1 - k_2) \Delta R}$$

where

$$Q = \frac{P_1(R) P_2(R + \Delta R)}{P_1(R + \Delta R) P_2(R)}$$

7.2.3.6b

Figure 7.2.3-8 is a typical received signal from the on-wavelength (lower curve) and off-wavelength (upper curve) laser beams as a function of range. The four signals are determined from analog signals as given in Figure 7.2.3-8. The absorption coefficients  $k_1$  and  $k_2$  have not been determined yet.

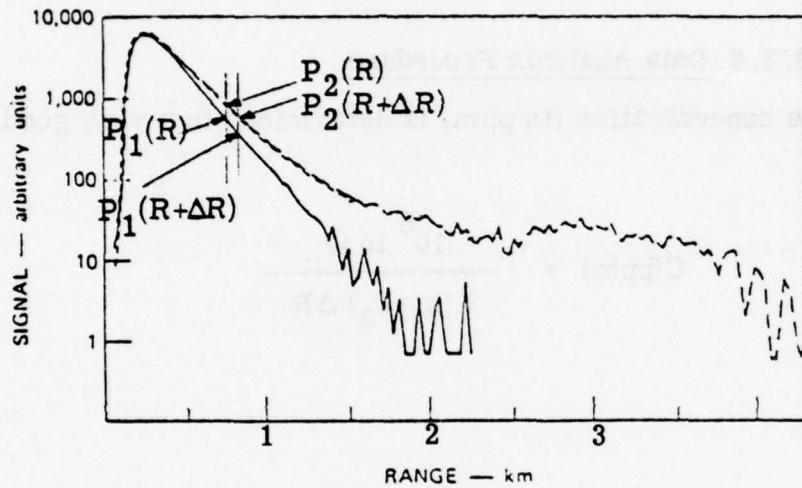


Figure 7.2.3-8. Analog Signals  $P_1(R)$ ,  $P_2(R)$ ,  $P_1(R+\Delta R)$  and  $P_2(R+\Delta R)$

#### 7. 2. 4 UV/Visible Differential Absorption

##### 7. 2. 4. 1 Principle of Operation

The measurement principle of ultraviolet/visible (UV/Visible) differential absorption is used to obtain range-resolved concentrations of  $\text{SO}_2$  and  $\text{NO}_2$ . Laser pulses at two different wavelengths in the 2000-5000 Å region are emitted and the backscattered signals are recorded. By differencing the wavelength-dependent and ratioing the time-dependent backscattered signals, the pollutants transmission can be determined as a function of range. The concentration of the pollutant is proportional to the logarithm of the monochromatic transmission. The proportionality factor is the monochromatic absorption coefficient which must be known.

##### 7. 2. 4. 2 System Description

The system consists of an energy source of one or two pulsed lasers, an optical system which may be common to the transmitter and receiver, and the receiver detector, electronics and data display. A block diagram indicating the essential elements of a typical UV/visible DAS system is shown in Figure 7. 2. 4. 1. It should be noted that no prototype UV/visible DAS system, using two lasers has been tested as yet. The maximum permissible energy (MPE) for laser systems has been promulgated by DHEW in 21CFR 1040.

##### 7. 2. 4. 3 System Parameters

###### Commercially Available Lasers

$\text{N}_2$  Gas Laser

Xe Gas Laser

Neodymium Yag Solid State Laser

RDA Ruby

Dye Lasers

7.2.4.3b

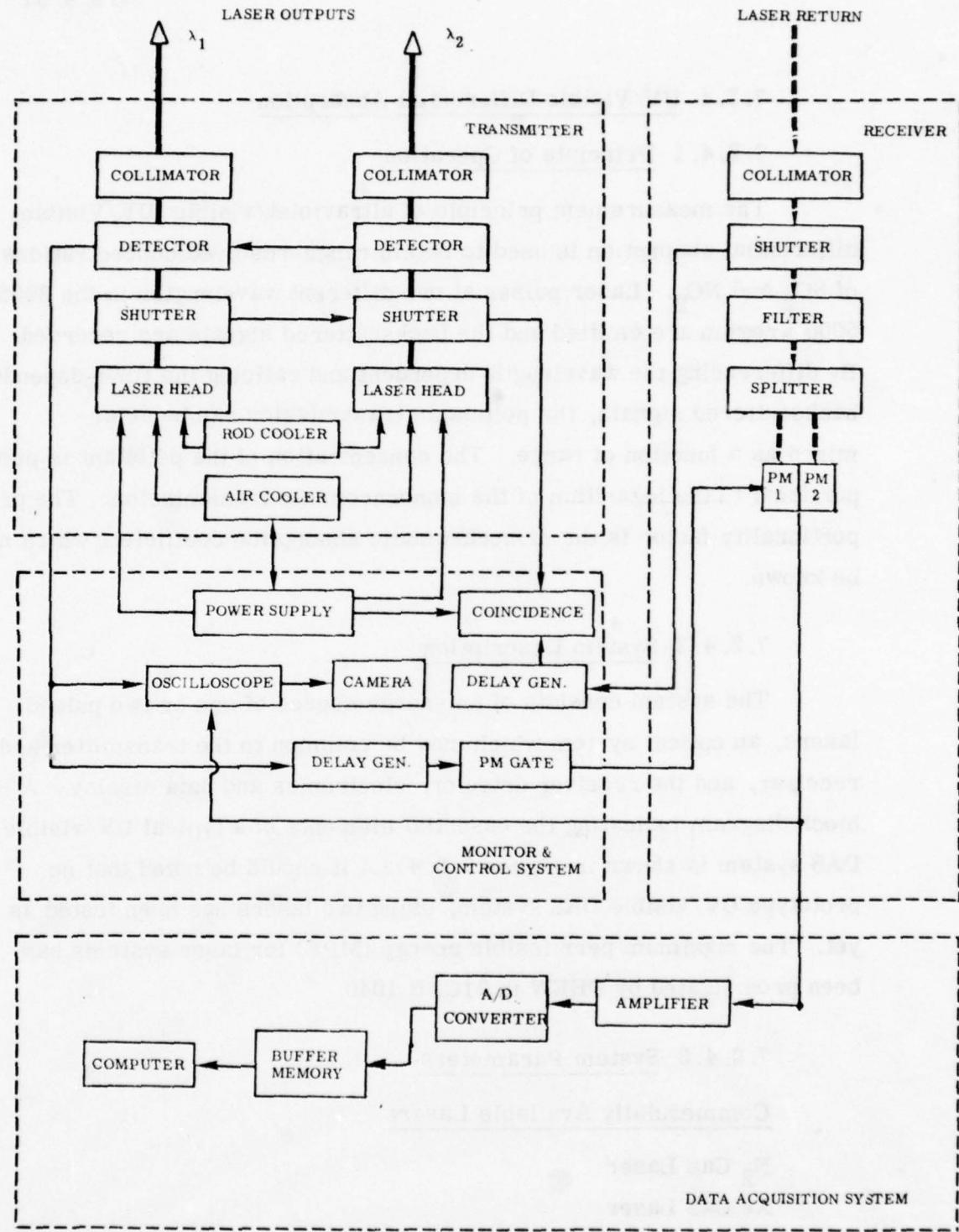


Figure 7.2.4-1. Conceptual Block Diagram of a UV/Visible DAS System (Based on Ref. 264).

Other lasers that have transitions in the UV/visible region, but are not commercially available at present, include Ar, Cl, S, Kr, Ne, F, O<sub>2</sub>, P, B, Pb, Si, Se, In, and I. (Refs. 265 and 257).

#### Operational Wavelengths

Have not been determined yet.

#### Laser Energy

For  $2500 < \lambda < 4000 \text{ \AA}$ , the maximum permissible laser energy ranges from  $6.2 \times 10^{-5}$  to  $.021 \text{ J/cm}^2$  for any pulse length. In the visible spectrum,  $4000 < \lambda < 7000 \text{ \AA}$ , the laser energy is dependent on the pulse length, ranging from  $5.2 \times 10^{-7} \text{ J/cm}^2$  for  $\tau_s < 10^{-5} \text{ sec}$  to  $7 \times 10^{-4} \text{ J/cm}^2$  for  $t_s = 1 \text{ sec}$ . These values are consistent with decreasing the laser power (W) for longer pulse durations. Shortest pulse duration of commercially available UV/visible lasers is in the nsec range. Available energy exceeds MPE by orders of magnitude.

#### Detector

Commercially available detectors are photomultipliers or Digicons having response curves S-13 or S-19. These tubes are very sensitive and have low noise figures. In general, the UV/visible receivers become shot and/or background noise limited.

#### Optics

Collecting Aperture	$A_o$
Solid Angle	$\Omega_o$
Optical Efficiency	$\eta_{opt}$
Detector Optics	$A_d \Omega_d (= A_o \Omega_o)$

These optical parameters are variables that must be chosen to fulfill the operational requirements (see below)

7.2.4.3d

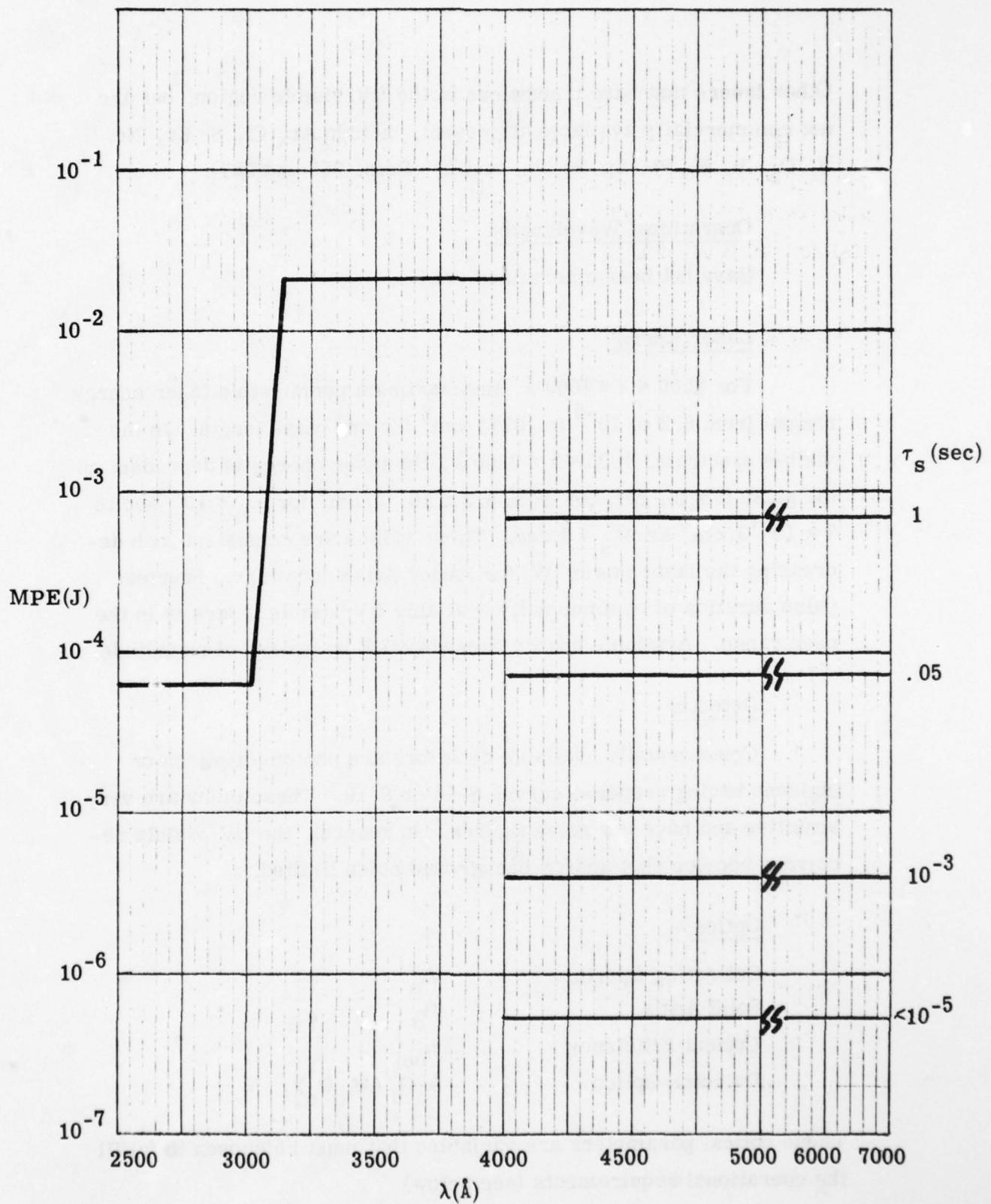


Figure 7.2.4-2. Maximum Permissible Laser Energy versus  $\lambda$  for Different Pulse Lengths

#### 7.2.4.4 Theoretical Performance Prediction

Based upon the selected system parameters, the performance can be predicted for a shot-noise-limited system. The signal-to-noise ratio for the determination of the pollutant concentration by UV/visible DAS is given by

$$\text{SNR} = \frac{\ln Q^1}{dP \sqrt{(1/P_1)^2 + (1/P'_1)^2 + (1/P_2)^2 + (1/P'_2)^2}}$$

where

$$\begin{aligned}\ln Q^1 &= \ln \frac{P_1 P'_2}{P'_1 P_2} \\ P_1 &= (G/R^2) e^{-2k_1 C R} \\ P'_1 &= (G/(R + \Delta R)^2) e^{-2k_1 C (R + \Delta R)} \\ P_2 &= (G/R^2) e^{-2k_2 C R} \\ P'_2 &= (G/(R + \Delta R)^2) e^{-2k_2 C (R + \Delta R)} \\ G &= \eta P_t \Delta R N(R) \beta A_o \\ dP &= (P_{\text{eff}} h\nu / \eta t_s)^{1/2}\end{aligned}$$

The SNR may be simplified, i.e.,

$$\text{SNR} = \frac{Q}{2} \left( \frac{\eta Q t_s}{h\nu} P_{\text{eff}} \right)^{1/2}$$

where

$$Q = 2(k_1 C_1 - k_2 C_2) \Delta R$$

$$P_{\text{eff}} = G \xi(R)$$

$$\xi(R) = R^{-2} e^{-2kCR}$$

In the following a stepwise description for the calculation of SNR is given

Step 1: Calculate: G

$$\text{Assume: } N(R)\beta \approx 8 \times 10^{-7} \text{ cm}^{-1} \text{ ster}^{-1}$$

$$\Delta R = 1500 \text{ cm}$$

$$P_t = 2 \times 10^{-1} \text{ J for } 3000 - 4000 \text{ \AA} \text{ and } 5.2 \times 10^{-6} \text{ J for } 4000 - 7000 \text{ \AA}, \text{ using } 10 \text{ cm}^2 \text{ laser beam area and pulse duration of } 10^{-7} \text{ sec.}$$

Result: Plot in Figure 7.2.4-3 and -4 shows G versus receiver aperture area  $A_o$  for three values of overall efficiency (optical and mechanical shutters)

Step 2: Calculate:  $\xi(R) = R^{-2} e^{-2kCR}$

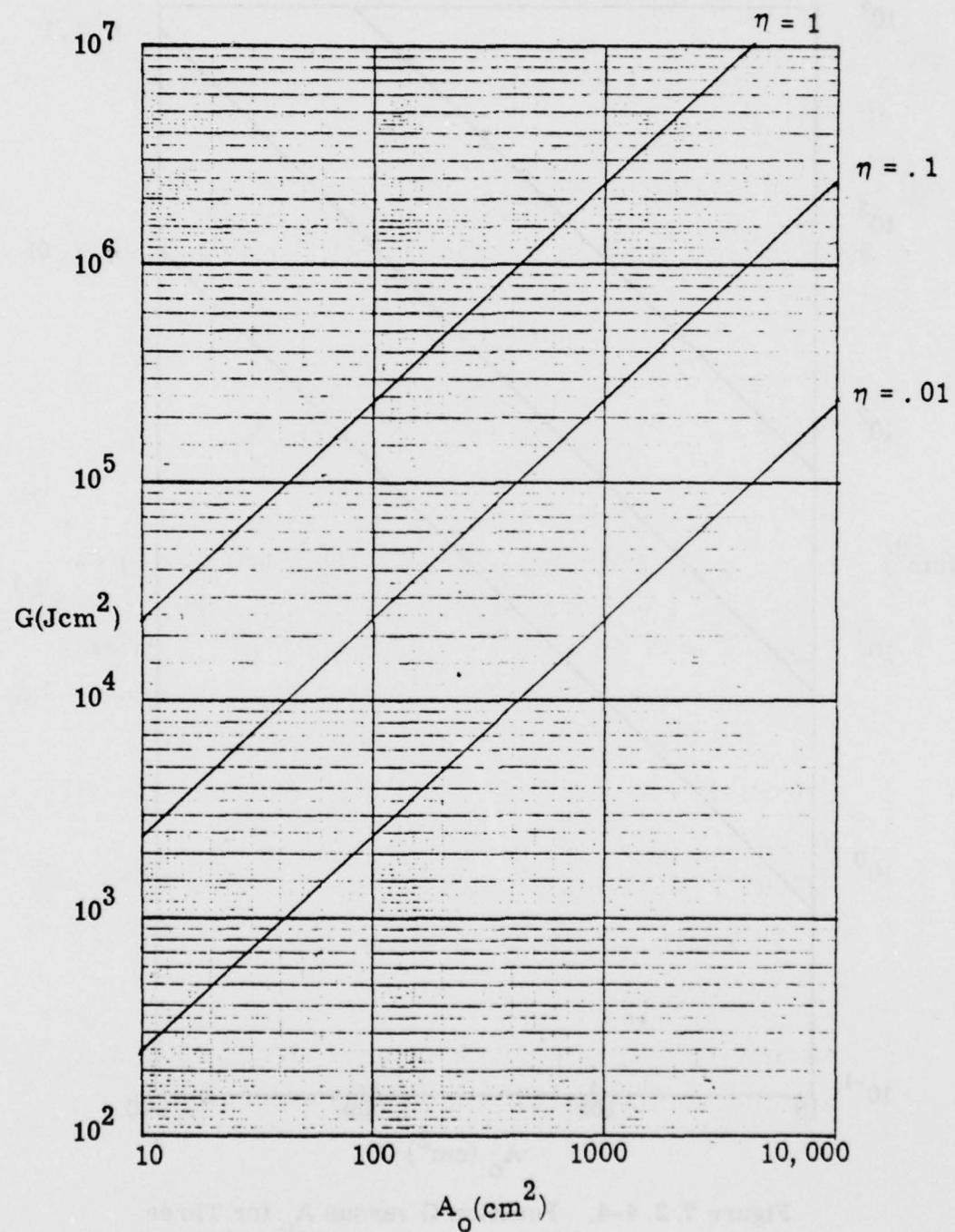
$$\text{Assume: } kC = 0, .3, 1, 3 \text{ km}^{-1}$$

Result: Plot in Figure 7.2.4-5 shows  $\xi(R)$  versus R for the above values of kC

Step 3: Calculate:  $P_{\text{eff}} = G \xi(R)$

Assume: Useful range of R between 100 and 1000 m

Result: Plot in Figure 7.2.4-6 which shows  $P_{\text{eff}}$  vs.  $\xi(R)$  for different values of G.



**Figure 7.2.4-3.** Function  $G$  versus  $A_0$  for Three Values of  $\eta$ , using  $\Delta R = 15 \text{ m}$ ,  $N(R)\beta = 8 \times 10^{-7} \text{ cm}^{-1}\text{ster}^{-1}$  and  $P_t = 2 \times 10^{-1} \text{ J}$  for  $10 \text{ cm}^2$  laser beam area, useful in range  $3000\text{-}4000 \text{ \AA}$ .

7.2.4.4d

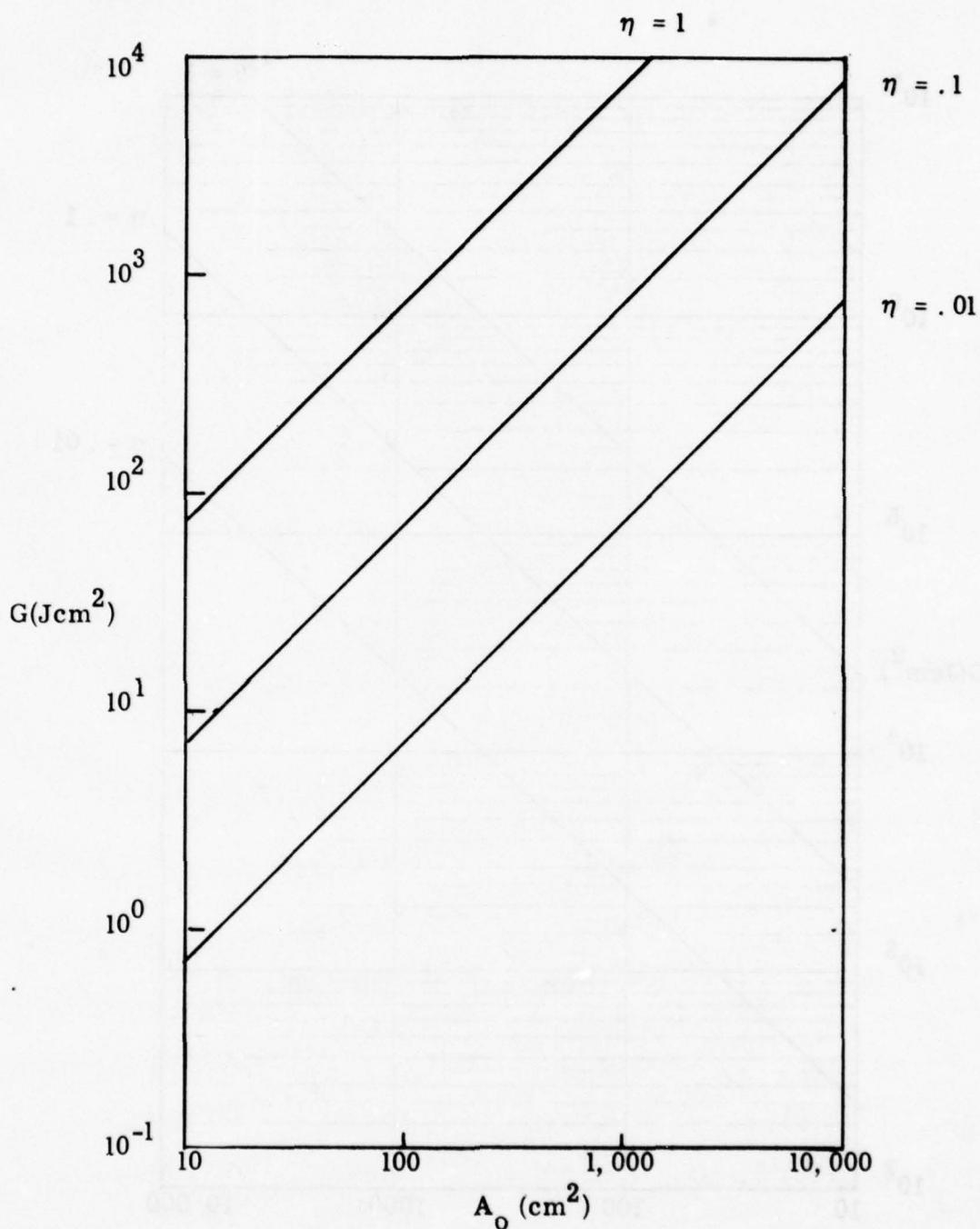


Figure 7.2.4-4. Function  $G$  versus  $A_0$  for Three Values of  $\eta$ , using  $\Delta R = 15 \text{ m}$ ,  $N(R)\beta = 8 \times 10^{-7} \text{ cm}^{-1} \text{ ster}^{-1}$  and  $P_t = 5.2 \times 10^{-6} \text{ J}$  for  $10 \text{ cm}^2$  laser beam area, useful in the visible region from  $4000$  to  $7000 \text{ \AA}$ .

7. 2. 4. 4e

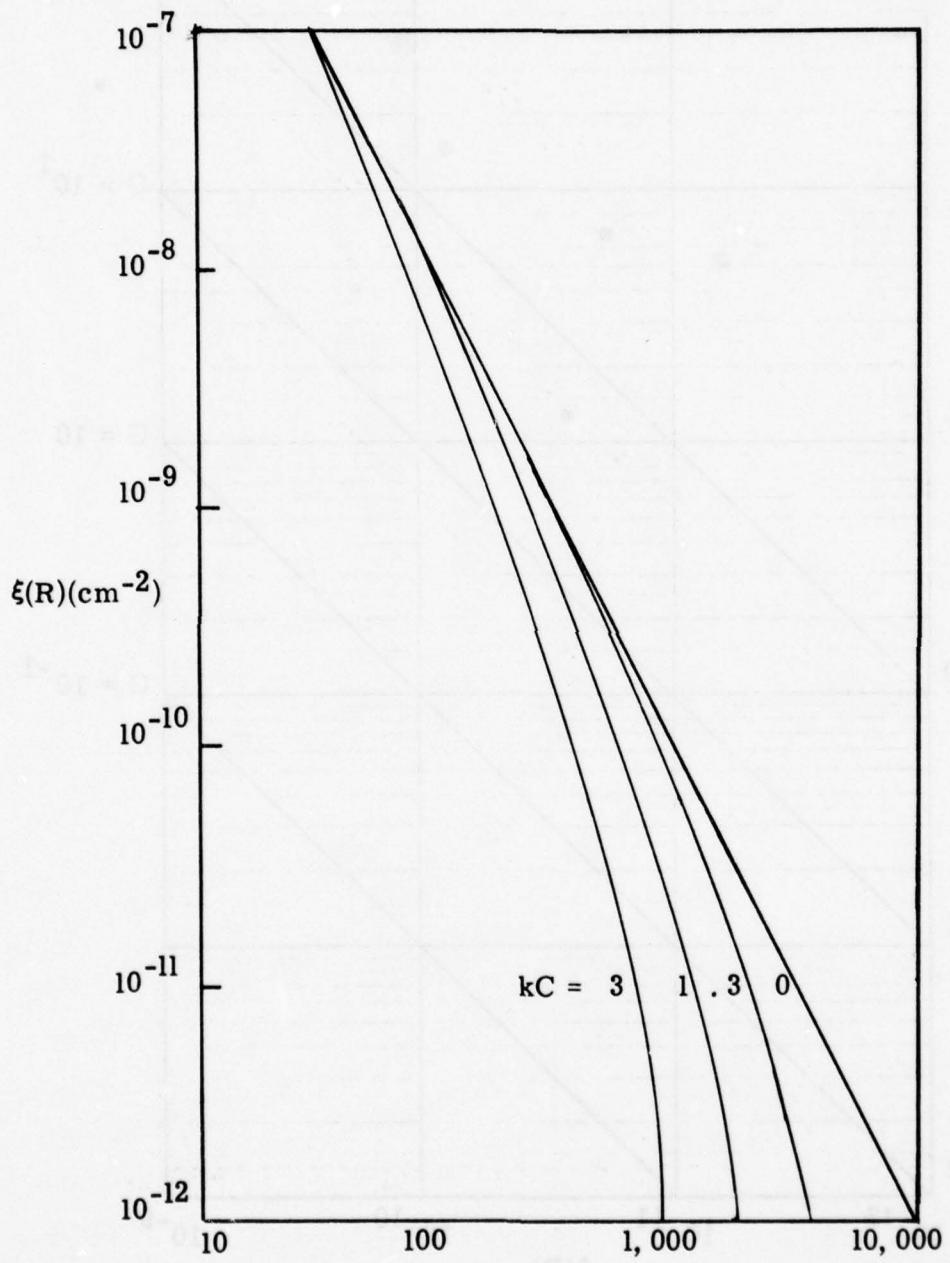


Figure 7. 2. 4-5. Function  $\xi(R)$  vs. Range for Different Values of  $kC(\text{km}^{-1})$

7. 2. 4. 4f

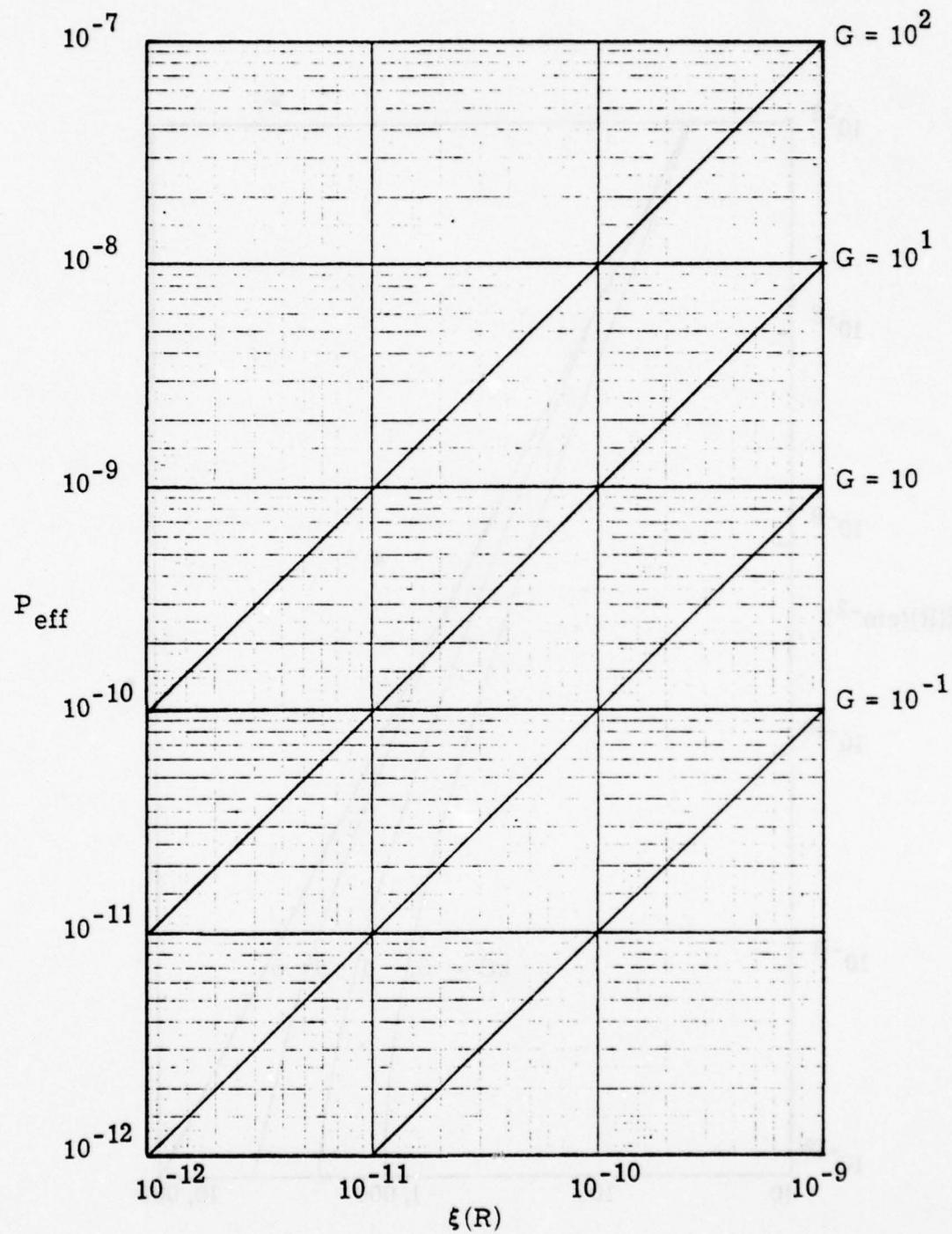


Figure 7. 2. 4-6.  $P_{\text{eff}}$  vs. the Function  $\xi(R)$  for Different Values of  $G$

Step 4: Calculate Q for (a)  $\text{SO}_2$  and (b)  $\text{NO}_2$

Assume:  $\Delta R = 0.015 \text{ km}$

Absorption coefficients of  $\text{SO}_2$  and  $\text{NO}_2$  for specific laser lines have not been determined yet. Calculation cannot be completed until these values are available.

Result: Q versus C to be plotted in Figure 7.2.4-7.

Step 5: Calculate: System Performance for NSR = 1, i.e.,

$$P_{\text{eff}} = \frac{h\nu}{\eta \text{tg}} \cdot \frac{4}{Q^2}$$

- (i) Calculate Q for desired concentration (Step 4, Figure 7.2.4-7)
- (ii) Locate intersection between  $\lambda$  and Q in Figure 7.2.4-8 and determine  $P_{\text{eff}}$
- (iii) For a given receiver optics area and overall efficiency, determine G from Figure 7.2.4-3 or 4.
- (iv) Find intersection between G and  $P_{\text{eff}}$  in Figure 7.2.4-8 and determine  $\xi(R)$ .
- (v) Find the distance R in Figure 7.2.4-5 for a given  $kC$ . The value of  $kC$  may be estimated by dividing 0.015 into Q, because  $Q \approx R \Delta R$  and  $\Delta R = 0.015 \text{ km}$ .

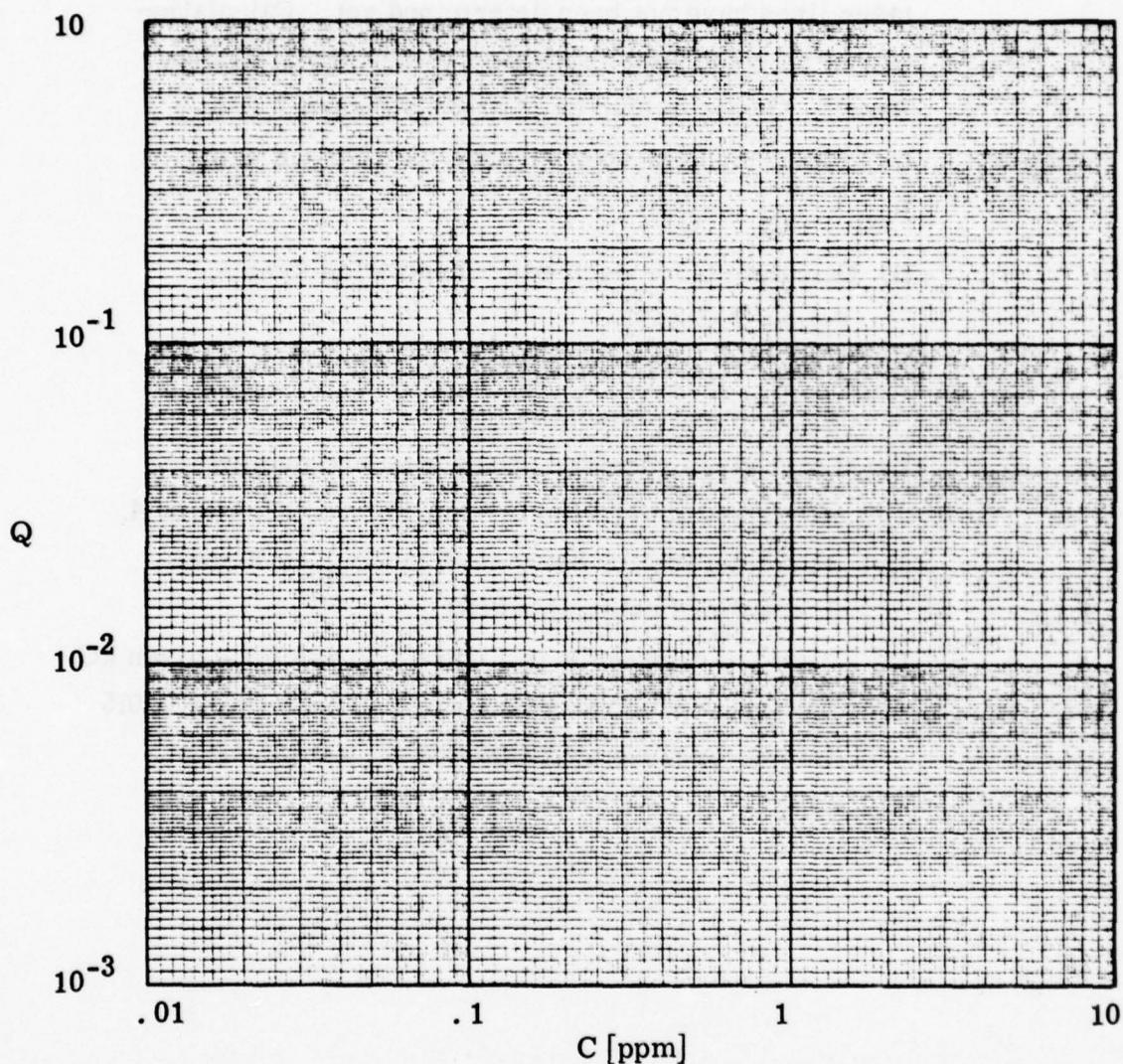


Figure 7.2.4-7.  $Q$  versus Concentration of  $\text{SO}_2$  and  $\text{NO}_2$  for a Resolution Element of 15 m.  
See Step 4, absorption coefficients required for this graph are not yet determined.

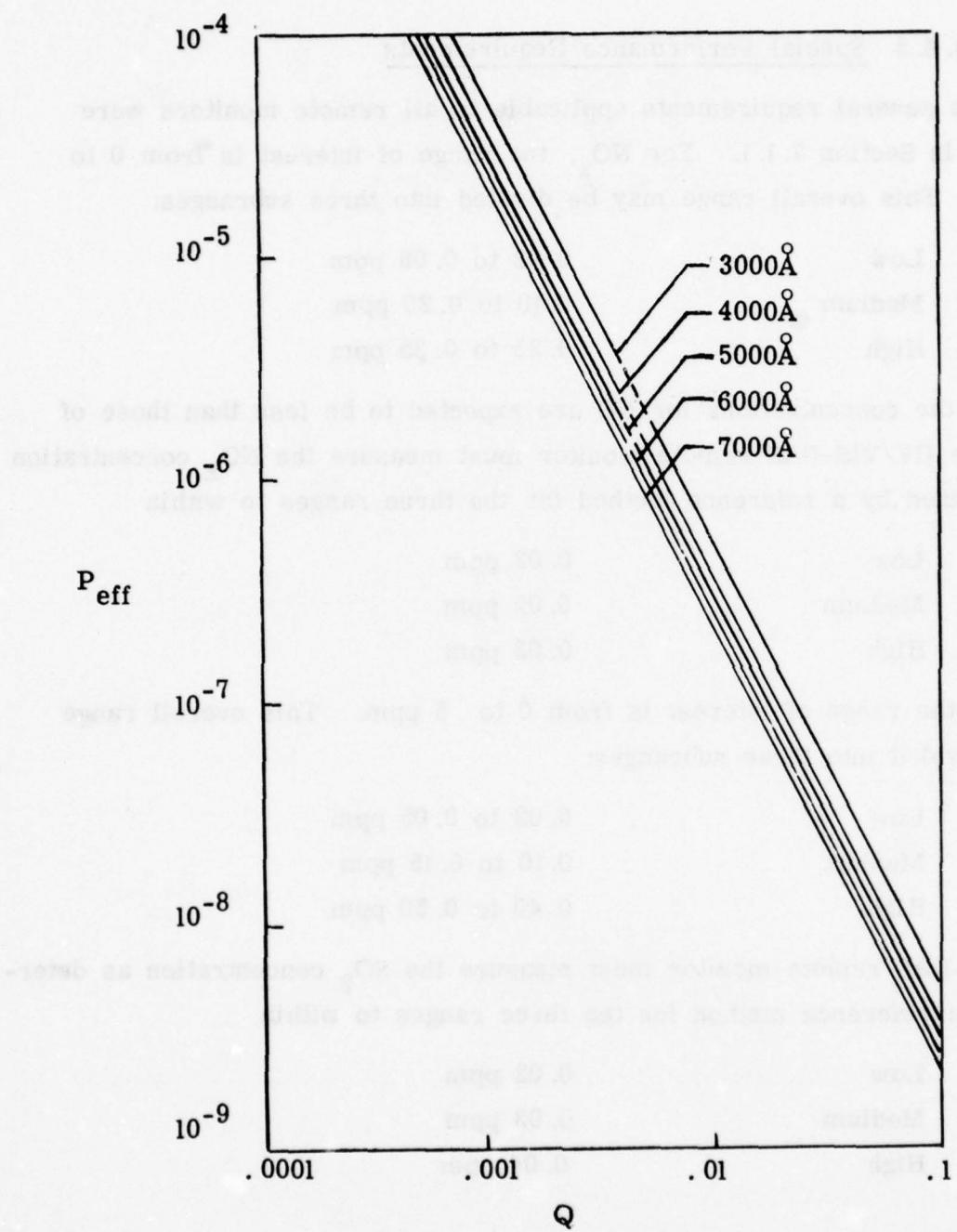


Figure 7. 2. 4-8.  $P_{\text{eff}}$  versus  $Q$  for  $3000 < \lambda < 7000 \text{\AA}$ .

## 7.2.4.5

### 7.2.4.5 Special Performance Requirements

The general requirements applicable to all remote monitors were described in Section 7.1.1. For NO<sub>x</sub>, the range of interest is from 0 to .35 ppm. This overall range may be divided into three subranges:

Low	0.02 to 0.08 ppm
Medium	0.10 to 0.20 ppm
High	0.25 to 0.35 ppm

However, the concentrations for NO are expected to be less than those of NO<sub>x</sub>. The UV/VIS-DAS remote monitor must measure the NO<sub>x</sub> concentration as determined by a reference method for the three ranges to within

Low	0.02 ppm
Medium	0.02 ppm
High	0.03 ppm

For SO<sub>2</sub>, the range of interest is from 0 to .5 ppm. This overall range may be divided into three subranges:

Low	0.02 to 0.05 ppm
Medium	0.10 to 0.15 ppm
High	0.40 to 0.50 ppm

The SWIR-DAS remote monitor must measure the SO<sub>2</sub> concentration as determined by a reference method for the three ranges to within

Low	0.02 ppm
Medium	0.03 ppm
High	0.04 ppm

#### 7.2.4.6a

##### 7.2.4.6 Data Analysis Procedure

The concentration (in ppm) is determined in a very good approximation by

$$C(\text{ppm}) = \frac{10^6 \ln Q}{2(k_1 - k_2) \Delta R}$$

where

$$Q = \frac{P_1(R) P_2(R + \Delta R)}{P_1(R + \Delta R) P_2(R)}$$

Figure 7.2.4-9 is a typical received signal from the on-wavelength (lower curve) and off-wavelength (upper curve) laser beams as a function of range. The four signals are determined from analog signals as given in Figure 7.2.4-9. The absorption coefficients  $k_1$  and  $k_2$  have not been determined yet.

7. 2. 4. 6b

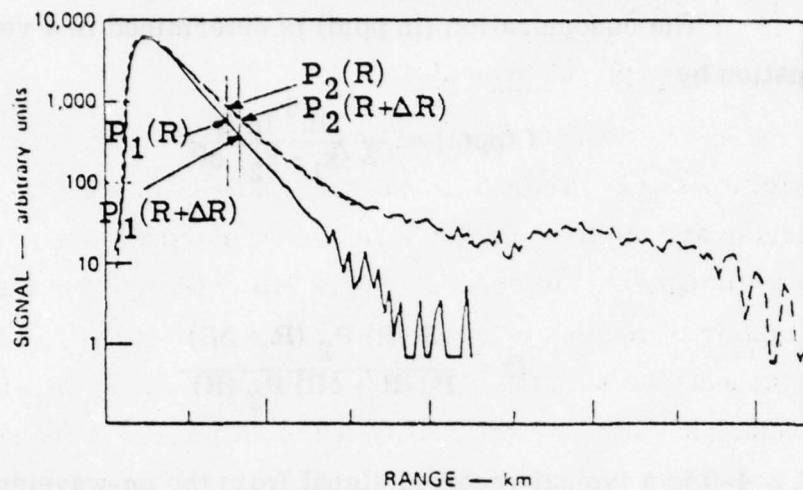


Figure 7.2.4-9. Analog Signals  $P_1(R)$ ,  $P_2(R)$ ,  $P_1(R+\Delta R)$  and  $P_2(R+\Delta R)$ .

## 7.2.5 LIDAR

### 7.2.5.1 Principle of Operation

The measurement principle of Lidar is used to obtain range-resolved opacities due to particulate matter. Laser pulses in the visible spectrum are emitted and the backscattered signals are recorded. By ratioing the time-dependent backscattered signals, the particulate matter transmission can be determined as a function of range. The concentration of the particles is proportional to the logarithm of the transmission. The proportionality factor is the extinction coefficient which must be known. Since the NAAQS is given in terms of mass density, relationships between opacity and mass density for different particles must first be established. Tentative relationships have been proposed as discussed in the Lidar section (in particular, Section 5.2.1.1).

### 7.2.5.2 System Description

The system consists of an energy source of one or two pulsed lasers, an optical system which may be common to the transmitter and receiver, and the receiver detector, electronics and data display. A block diagram indicating the essential elements of a typical system (Figure 7.2.5-1) is basically the same as for UV/VIS DAS, except that only one wavelength instead of two is required. The maximum permissible energy (MPE) for laser systems has been promulgated by DHEW in 21CFR1040.

7.2.5.2b

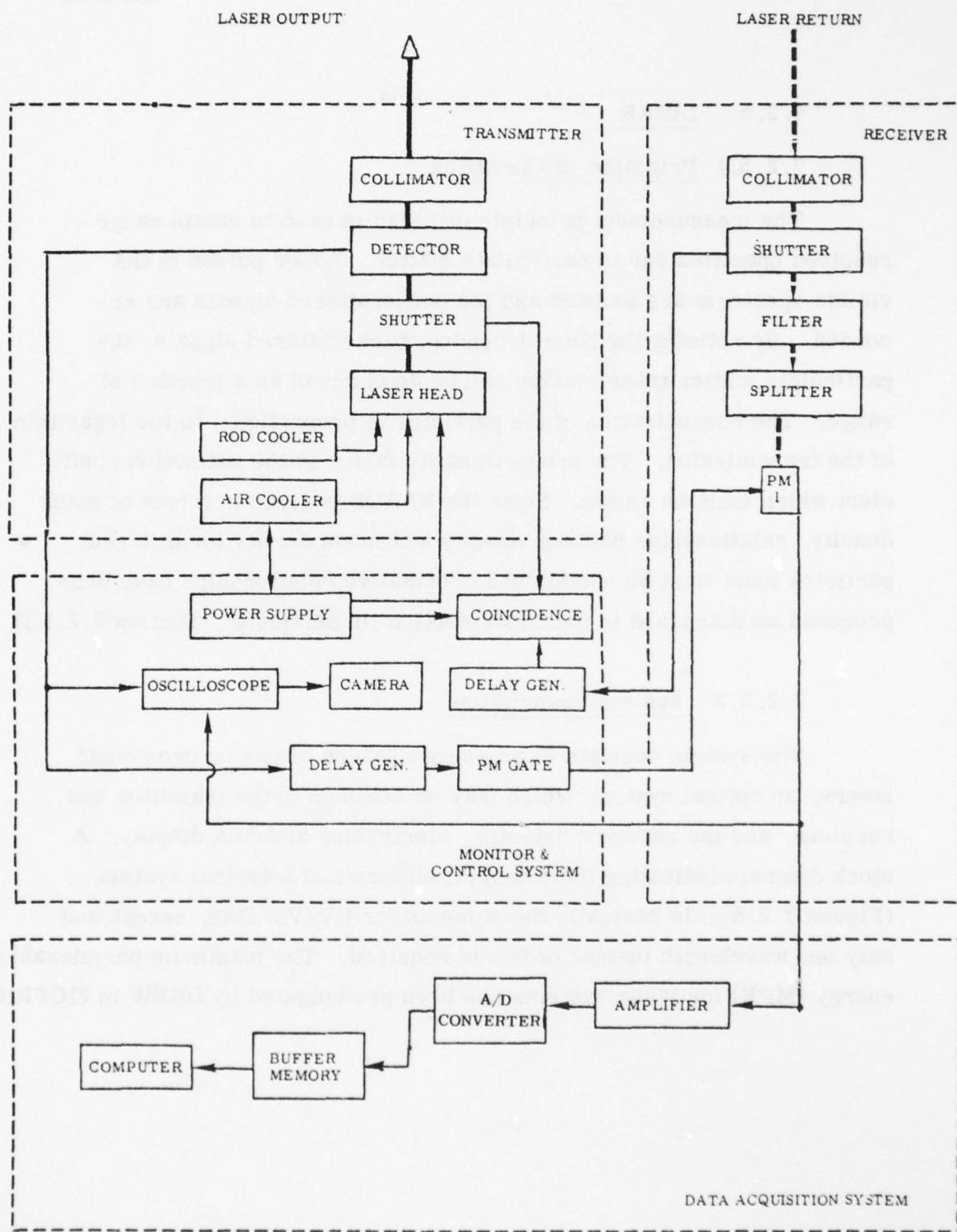


Figure 7.2.5-1. Conceptual Block Diagram of a LIDAR System  
(Based on Ref. 264).

7. 2. 5. 3 System ParametersCommercially Available Lasers

Ar Gas Laser

Ar/Kr Gas Laser

Ne Gas Laser

Kr Gas Laser

Xe Gas Laser

Neodymium Yag Solid State Laser

Ruby Solid State Laser

Dye Laser

Operational Wavelengths

Laser	$\lambda^o(A)$	$P_{max}(J)$	$\tau_s(ns)$
Ar	4579-5395	$10^{-4}$	6000
Ar/Kr	4580-6470	$10^{-6}$	15
Kr	4762-6764	$6 \times 10^{-5}$	40
Ne	5401	$3 \times 10^{-5}$	3
Xe	3645-5395	$10^{-4}$	500
Neod-Yag	5320	$4 \times 10^{-2}$	15
Ruby	6943	1	150

Potential interfering atmospheric lines are listed in Refs. 265 and 266.

Laser Energy $5.2 \times 10^{-7} J/cm^2$  for pulses  $< 10^{-5}$  sec.Shortest pulse duration of commercially available CO<sub>2</sub> lasers is in the nsec range. Available energy exceeds MPE by orders of magnitude.

### Detector

Commercially available detectors are photomultipliers or Digicons having the response curve S-19. These tubes are very sensitive and have low noise figures. In general, the UV/visible receivers become shot or background noise limited.

### Optics

Collecting Aperture	$A_o$
Solid Angle	$\Omega_o$
Optical Efficiency	$\eta_{opt}$
Detector Optics	$A_d \Omega_d (= A_o \Omega_o)$

These optical parameters are variables that must be chosen to fulfill the operational requirements (see below).

### 7.2.5.4 Theoretical Performance Prediction

Based upon the selected system parameters, the performance can be predicted for a shot-noise-limited system. The signal-to-noise ratio for the determination of the opacity due to particles is given by

$$SNR = \frac{\ln Q^1}{dP \sqrt{(1/P_1)^2 + (1/P'_1)^2}}$$

where

$$\begin{aligned}\ln Q^1 &= \ln \frac{P}{P'} \\ P &= (G/R^2) e^{-2\beta_{ext} R} \\ P' &= (G/(R + \Delta R))^2 e^{-2\beta_{ext}(R + \Delta R)}\end{aligned}$$

$$\begin{aligned} G &= \eta P_t \Delta R N(R) \beta A_o \\ dP &= (P_{\text{eff}} h\nu / \eta Q t_s)^{1/2} \end{aligned}$$

The SNR may be simplified, i. e.,

$$\text{SNR} = \frac{Q}{2} \left( \frac{\eta Q t_s}{h\nu} P_{\text{eff}} \right)^{1/2}$$

where

$$\begin{aligned} Q &= 2 \beta_{\text{ext}} \Delta R \\ P_{\text{eff}} &= G \xi(R) \\ \xi(R) &= R^{-2} e^{-2\beta_{\text{ext}} R} \end{aligned}$$

where  $\beta_{\text{ext}}$  is the extinction coefficient.

In the following a stepwise description for the calculation of SNR is given

Step 1: Calculate: G

Assume:  $N(R)\beta \approx 8 \times 10^{-7} \text{ cm}^{-1} \text{ ster}^{-1}$

$\Delta R = 1500 \text{ cm}$

$P_t = 5.2 \times 10^1 \text{ W}$  for  $10 \text{ cm}^2$  laser beam area  
and  $4000-7000 \text{ \AA}$

Result: Plot in Figure 7.2.5-2 shows G versus receiver aperture area  $A_o$  for three values of overall efficiency (optical and mechanical shutters)

Step 2: Calculate:  $\xi(R) = R^{-2} e^{-2\beta_{\text{ext}} R}$

Assume:  $\beta_{\text{ext}} = 0, .3, 1, 2 \text{ km}^{-1}$

Result: Plot in Figure 7.2.5-3 shows  $\xi(R)$  versus R for the above values of  $\beta_{\text{ext}}$

7. 2. 5. 4c

- Step 3: Calculate:  $P_{\text{eff}} = G \xi(R)$   
 Assume: Useful range of  $R$  between 100 and 1000 m.  
 Result: Plot in Figure 7. 2. 5-4 which shows  $P_{\text{eff}}$  vs.  $\xi(R)$  for different values of  $G$ .
- Step 4: Calculate:  $Q$  for particulate matter  
 Assume:  $\Delta R = 15$  km. Use approximate relationship between mass density and total extinction coefficient as outlined in Section 5. 2. 1. 1 in this report.  
 Result: Plot in Figure 7. 2. 5-5 shows  $Q$  for particulate matter versus mass density for  $\Delta R = 15$  km. also following table, where  $Q$  is given as functions of wavelength and mass density.

$\lambda$	$\rho = 10$	30	100	300	1000
4000	$1.70^{-3}$	$3.46^{-3}$	$9.63^{-3}$	$2.73^{-2}$	$8.80^{-2}$
4500	$1.14^{-3}$	$2.71^{-3}$	$8.17^{-3}$	$2.38^{-2}$	$7.85^{-2}$
5000	$8.37^{-4}$	$2.24^{-3}$	$7.15^{-3}$	$2.12^{-2}$	$7.02^{-2}$
5500	$6.57^{-4}$	$1.93^{-3}$	$6.38^{-3}$	$1.91^{-2}$	$6.36^{-2}$
6000	$5.11^{-4}$	$1.67^{-3}$	$5.74^{-3}$	$1.74^{-2}$	$5.80^{-2}$
6500	$4.30^{-4}$	$1.50^{-3}$	$5.24^{-3}$	$1.59^{-2}$	$5.34^{-2}$
7000	$3.51^{-4}$	$1.34^{-3}$	$4.81^{-3}$	$1.47^{-2}$	$4.94^{-2}$

- Step 5: Calculate: System Performance for SNR = 1, i. e.,  $P_{\text{eff}} = \frac{h\nu}{\eta t g} \frac{4}{Q^2}$
- Calculate  $Q$  for desired mass density and wavelength (Step 4, Figure 7. 2. 5-5)
  - Locate intersection between  $\lambda$  and  $Q$  in Figure 7. 2. 5-6 and determine  $P_{\text{eff}}$ . If intersection is not within the limits of the graph, the measurement is not feasible beyond 100 m.

7.2.5.4c<sub>1</sub>

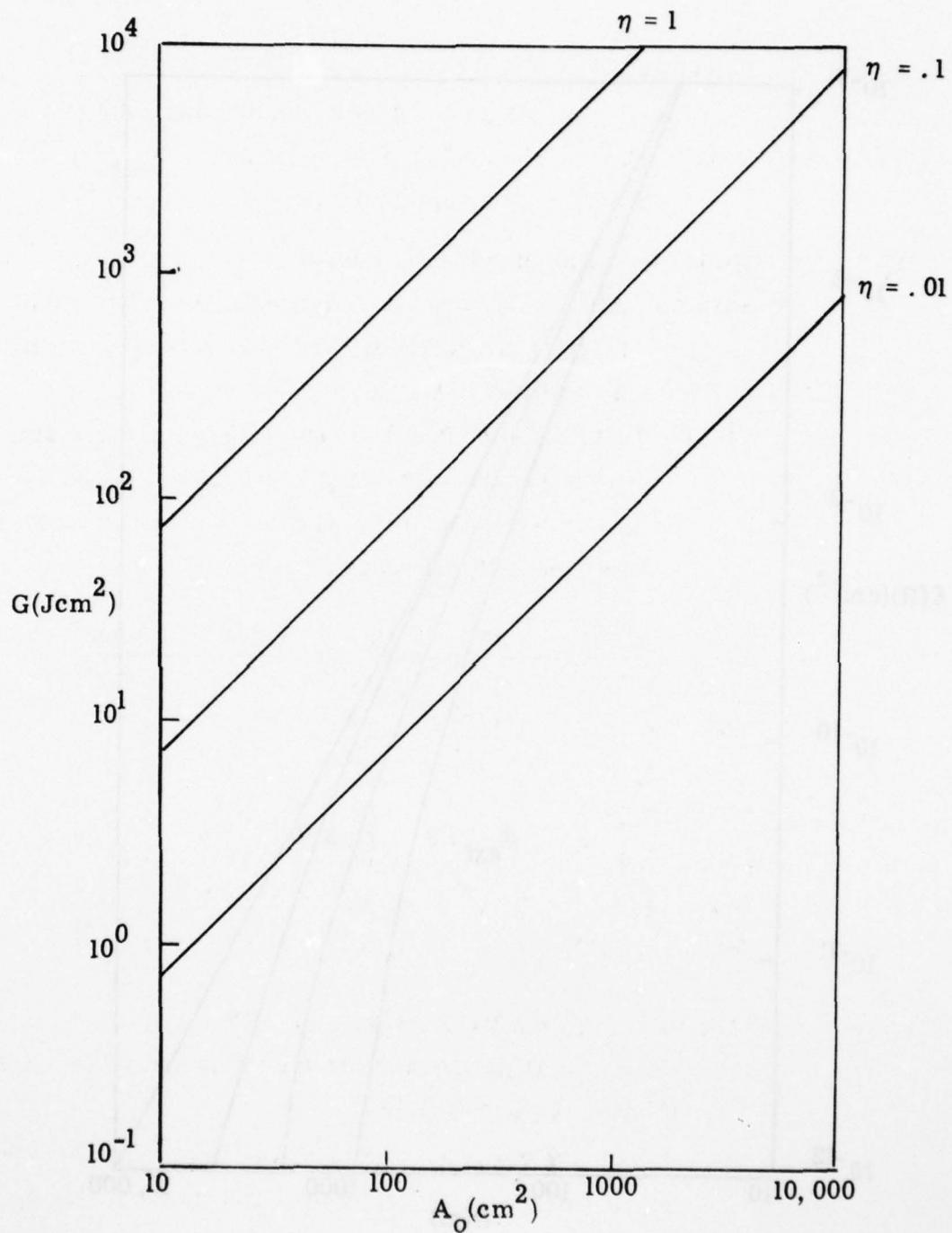


Figure 7.2.5-2 Function  $G$  versus  $A_0$  for Three Values of  $\eta$ , using  $\Delta R = 15 \text{ m}^{\frac{1}{2}}$ ,  $N(R)\beta = 8 \times 10^{-7} \text{ cm}^{-1} \text{ ster}^{-1}$  and  $P_t = 5.2 \times 10^{-5} \text{ J}$  for  $10 \text{ cm}^2$  laser beam area, useful in the visible region from  $4000$  to  $7000 \text{ \AA}$ .

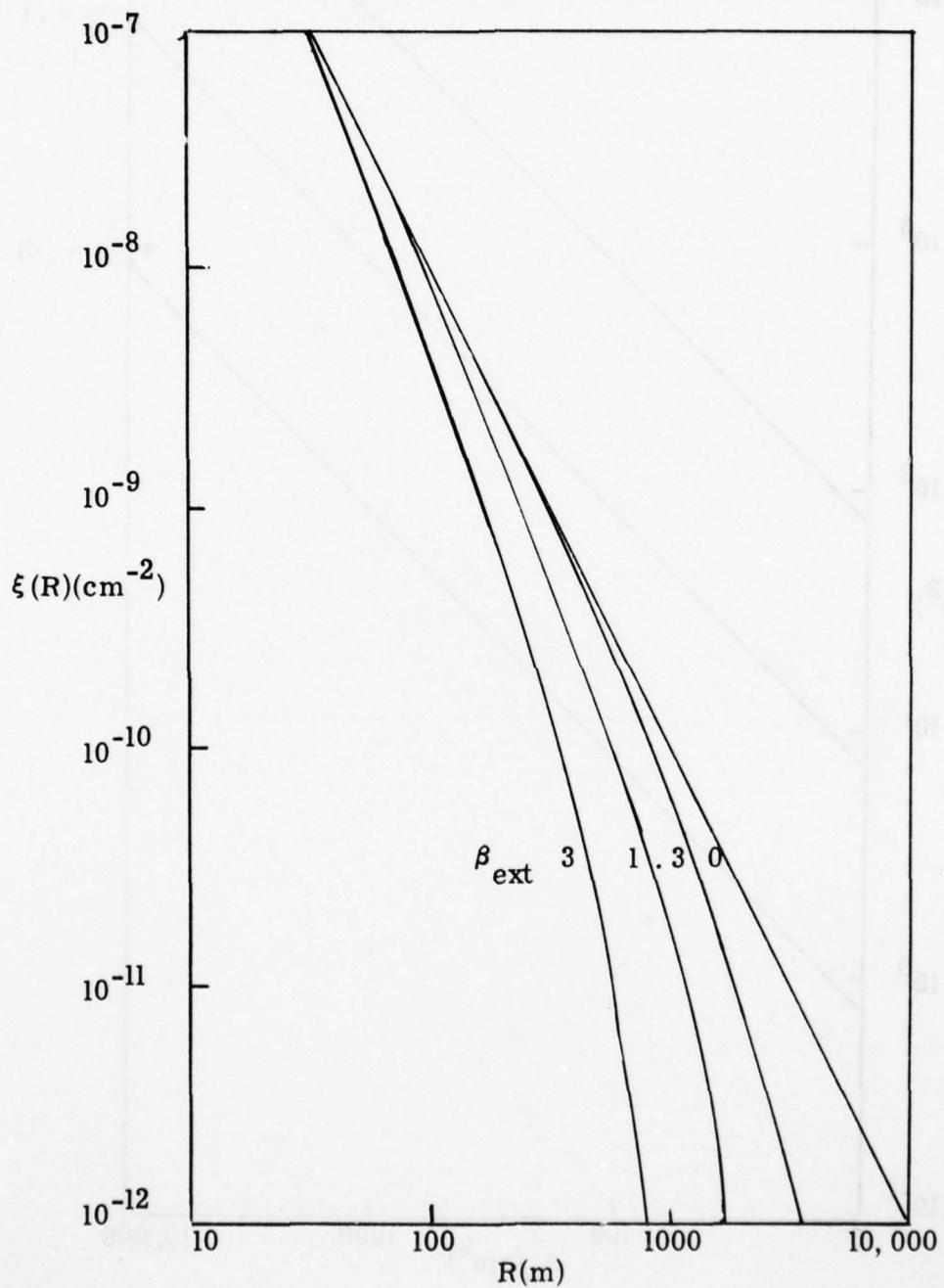


Figure 7.2.5-3. Function  $\xi(R)$  vs. Range for Different Values of  $\beta_{\text{ext}}$  (km $^{-1}$ )

7. 2. 5. 4e

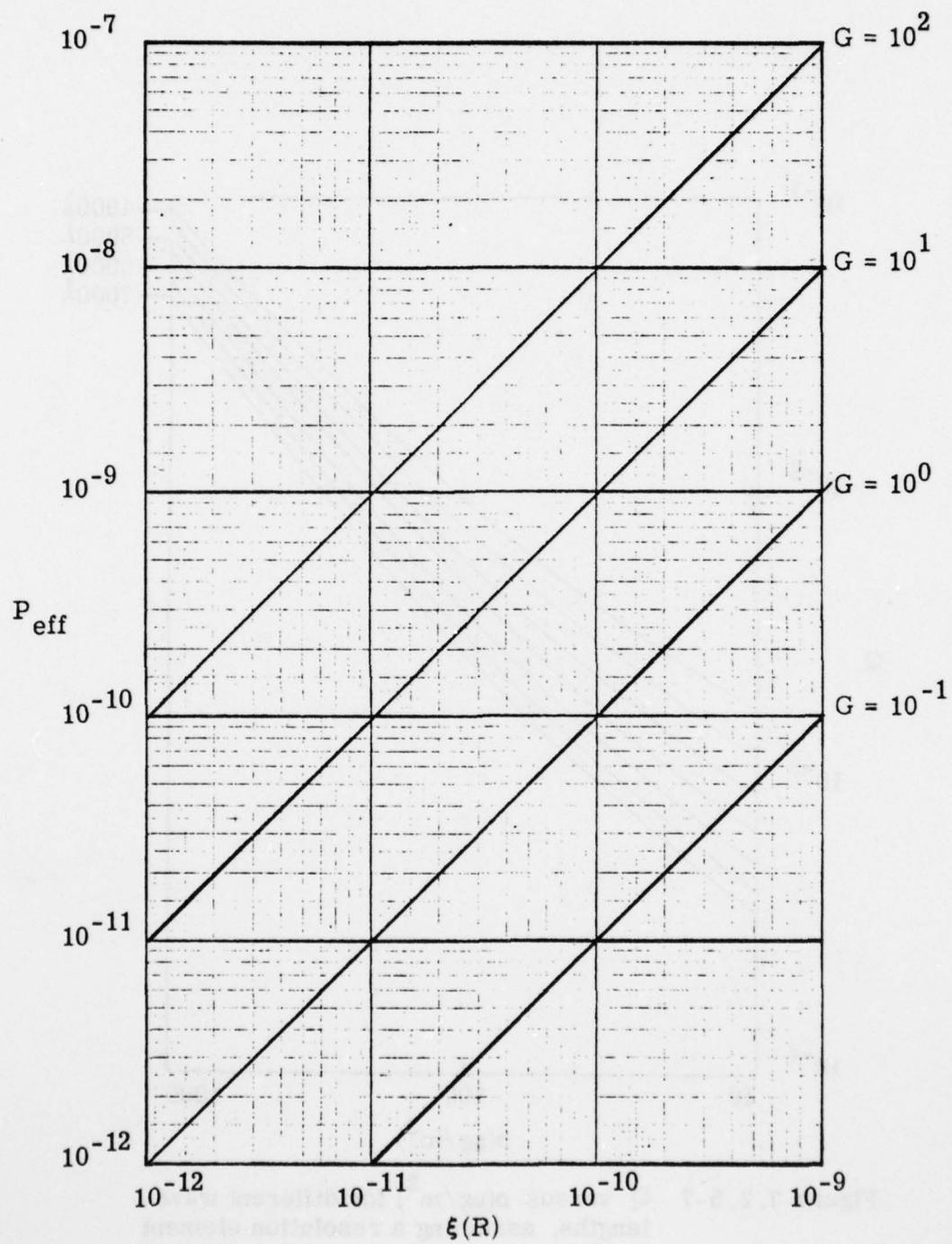


Figure 7.2.5 -4  $P_{\text{eff}}$  vs. the Function  $\xi(R)$  for Different Values of  $G$

7.2.5.4f

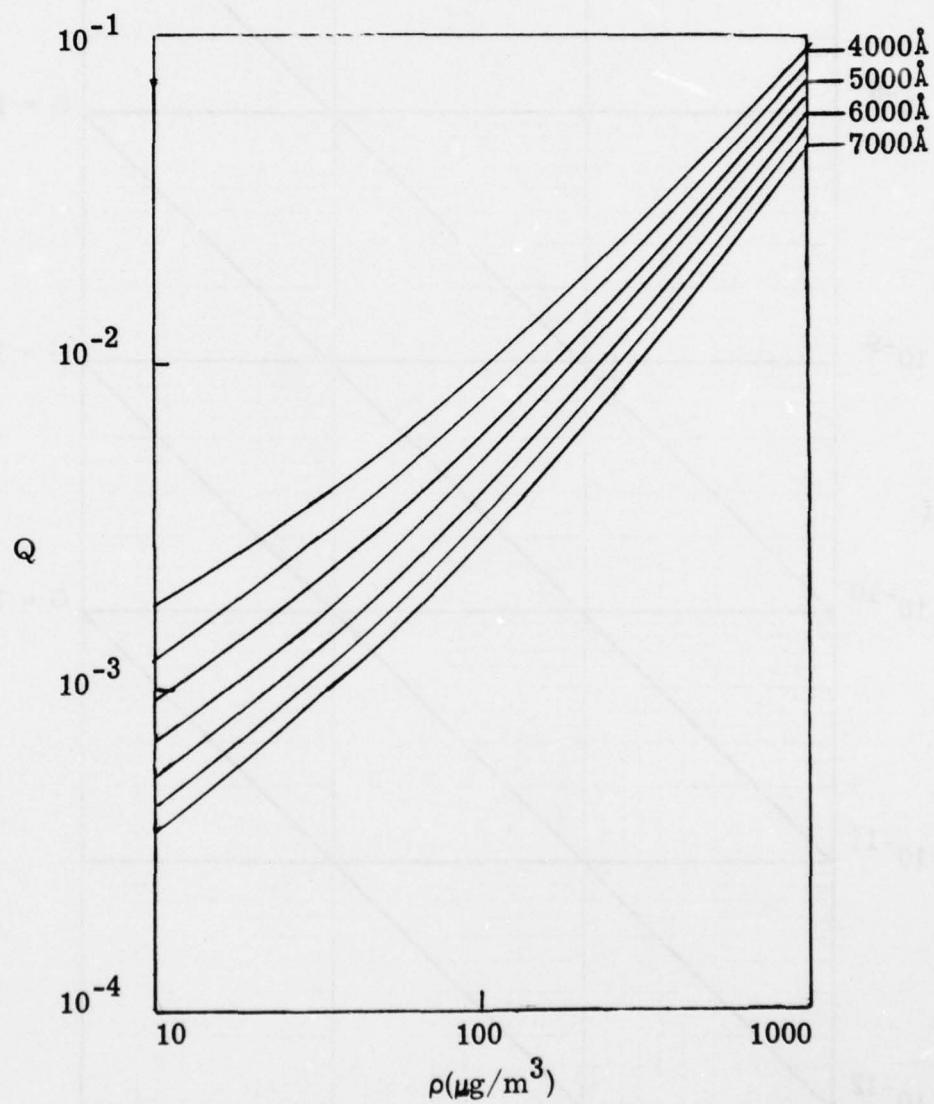


Figure 7.2.5-7  $Q$  versus  $\rho(\mu\text{g}/\text{m}^3)$  for different wavelengths, assuming a resolution element of 15 m and  $\eta_Q = 0.5$

- iii) For a given receiver optics area and overall efficiency, determine G from Figure 7.2.5-2.
- iv) Find intersection between G and  $P_{\text{eff}}$  in Figure 7.2.5-4 and determine  $\xi(R)$ .
- v) Find distance R in Figure 7.2.5-3 for a given  $\beta_{\text{ext}}$ . The value of  $\beta_{\text{ext}}$  may be estimated by dividing 0.015 into Q, because  $Q \approx \beta_{\text{ext}} \Delta R$  and  $\Delta R = 0.015 \text{ km}$ .

Example: (i) For a mass density of  $300 \mu\text{g}/\text{m}^3$ , one finds in Figure 7.2.5-5  $Q = 1.8 \times 10^{-2}$  for  $\lambda = 5000 \text{ \AA}$ . (ii) In Figure 7.2.5-6, one finds  $P_{\text{eff}} = 9 \times 10^{-8}$ . (iii) In Figure 7.2.5-4, one finds  $G = 240 \text{ W cm}^2$  for  $\eta = .1$  and  $A_o = 1000 \text{ cm}^2$ . (iv) The intersection in Figure 7.2.5-4 between  $P_{\text{eff}} = 9 \times 10^{-8} \text{ W}$  and  $G = 240 \text{ W cm}^2$  results in  $\xi(R) \approx 5 \times 10^{-10} \text{ cm}^{-2}$ . (v) For  $\beta_{\text{ext}} = 1.8 \times 10^{-2}/0.015 = 1.2$ , R becomes about 300 m.

#### 7.2.5.5 Special Performance Requirements

The general requirements applicable to all remote monitors were described in Section 7.1.1. For particulate matter (TSP), the range of interest is from 60 to  $350 \mu\text{g}/\text{m}^3$ . This overall range may be divided into three subranges:

Low	$60 \text{ to } 90 \mu\text{g}/\text{m}^3$
Medium	$150 \text{ to } 200 \mu\text{g}/\text{m}^3$
High	$250 \text{ to } 350 \mu\text{g}/\text{m}^3$

The Lidar monitor must measure the TSP density as determined by a reference method for the three ranges to within

Low	$20 \mu\text{g}/\text{m}^3$
Medium	$30 \mu\text{g}/\text{m}^3$
High	$40 \mu\text{g}/\text{m}^3$

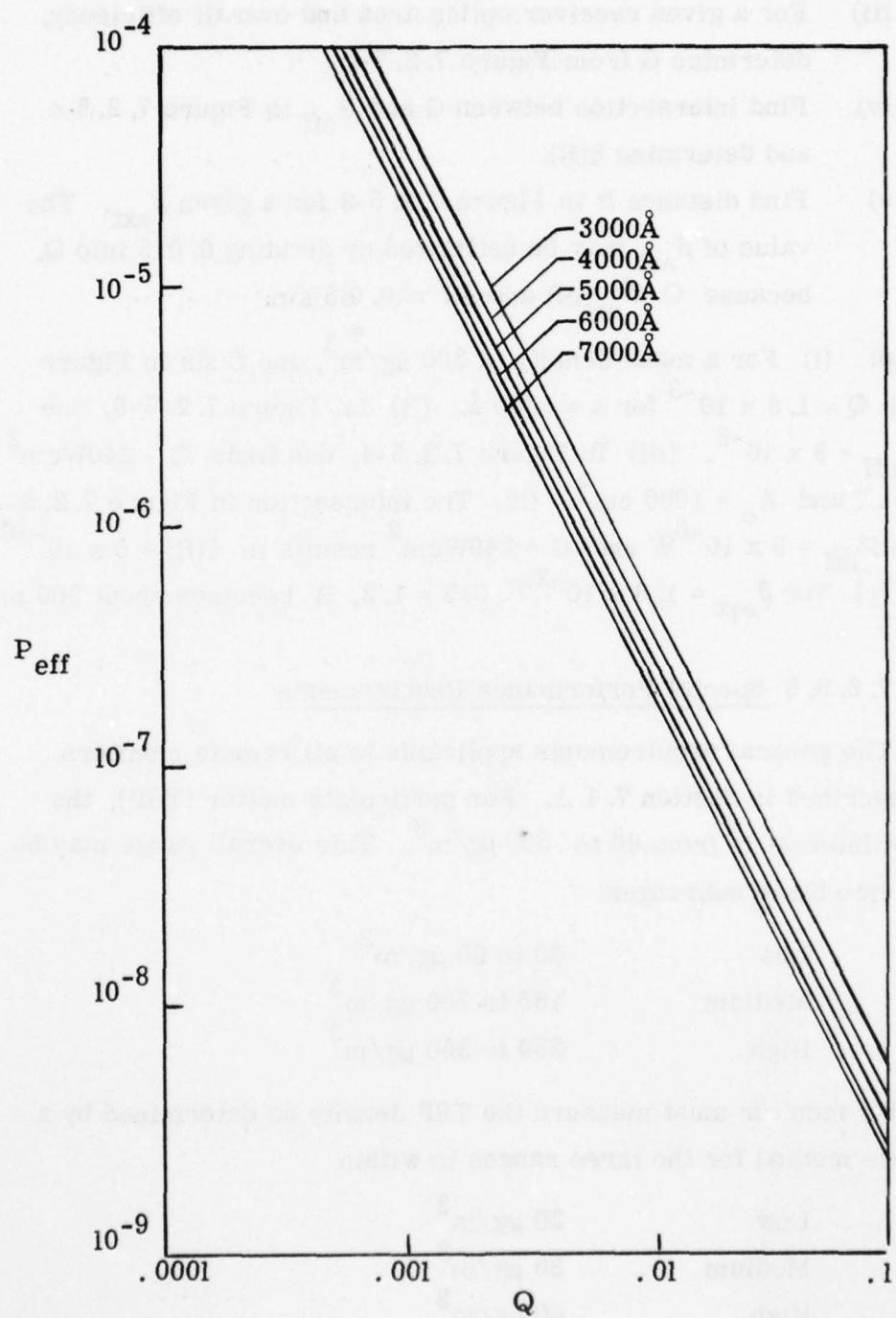


Figure 7.2.5-6  $P_{\text{eff}}$  versus  $Q$  for  $3000 < \lambda < 7000 \text{\AA}$ .

7.2.5.5b  
7.2.5.6a

However, as was shown in Section 5.2.1.1, the TSP density is not measured directly by an optical method. Thus, either the relationship between extinction and mass density must be firmly established or EPA develops a NAAQS based on the extinction due to TSP.

#### 7.2.5.6 Data Analysis Procedure

The mass density of TSP is determined approximately by

$$\rho(\mu\text{g}/\text{m}^3) = \frac{\beta_{\text{ext}} - \beta_R(\lambda) + 64.0/\lambda(\text{\AA}) - 3.36 \times 10^{-4}}{[12.0/\lambda(\text{\AA})] - 6.3 \times 10^{-5}}$$

where

$$\beta_{\text{ext}} = \frac{\ln Q}{2 \Delta R}$$

Q =  $P(R)/P(R+\Delta R)$ , as determined according to Figure 7.2.5-7, which shows a typical received signal as a function of range.

$\beta_R(\lambda)$  = Rayleigh attenuation coefficient as given in Figure 7.2.5-8

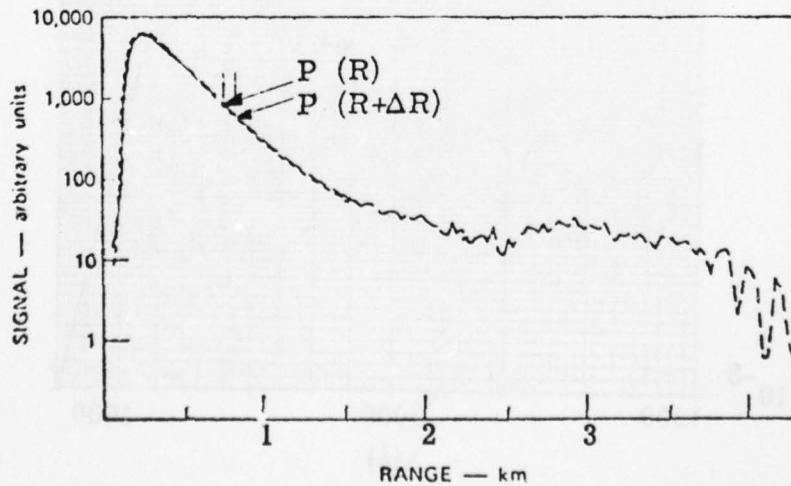


Figure 7.2.5-7. Analog Signals  $P(R)$ , and  $P(R+\Delta R)$  vs. Range

7. 2. 5. 6b

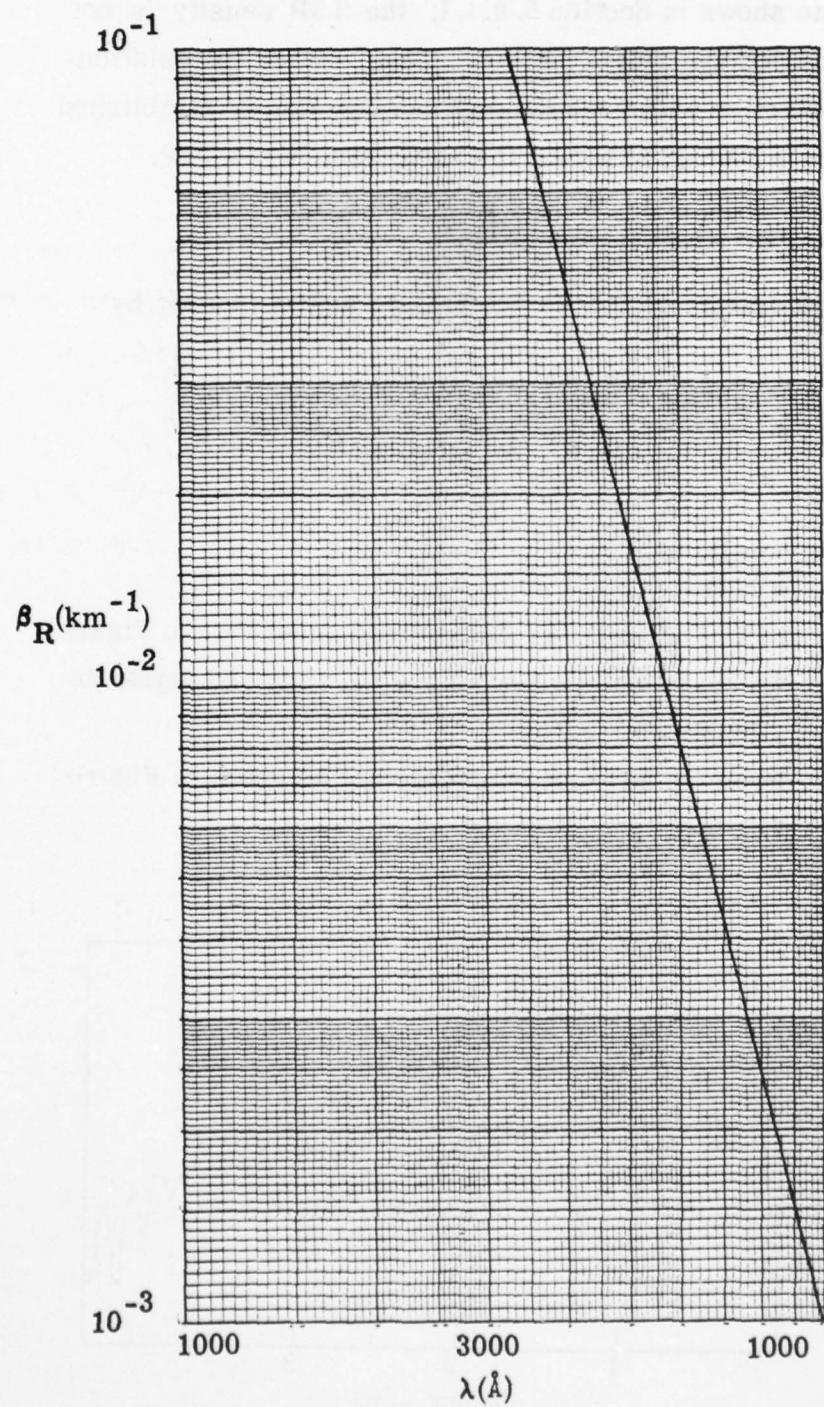


Figure 7. 2. 5-8. Rayleigh Attenuation Coefficient vs.  $\lambda$

**7. 3    Remote Monitors Providing Line Average Data**

**7. 3. 1    LWIR Long-Path with Laser Source**

**7. 3. 1. 1    Principle of Operation**

The measurement principle of long wavelength infrared (LWIR) long-path transmission is used to obtain line averaged concentrations of ozone and certain hydrocarbons. Laser beams at two different wavelengths in the 8-12  $\mu\text{m}$  region are emitted and the transmitted signals are recorded by a receiver. By differencing the wavelength-dependent signals, the average absorption of the pollutants can be determined. The concentration of the pollutant is proportional to the logarithm of the monochromatic transmission. The proportionality factor is the monochromatic absorption coefficient which must be known.

**7. 3. 1. 2    System Description**

The system consists of one or two lasers as transmitter, collecting optics, which may be common to the transmitter and receiver, a detector, electronics and data display. A block diagram indicating the essential elements of a typical system using direct detection (dd) is shown in Figure 7. 3. 1-1. In order to use a heterodyn detection (hd) system, a frequency shift must be provided within the instrument (see Figure 7. 3. 1-2).

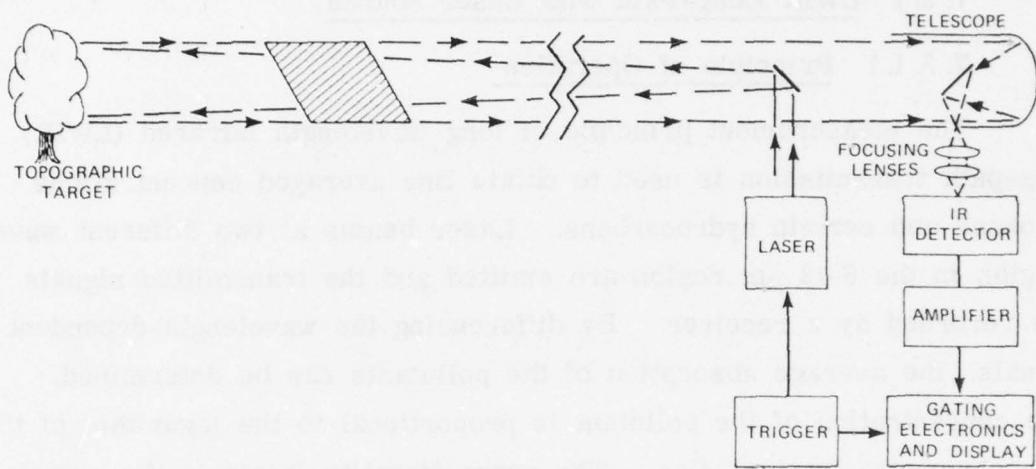


Figure 7.3.1-1. Block Diagram for LWIR Long-Path System Using Single Laser and Direct Detection (adopted from Ref. 249).

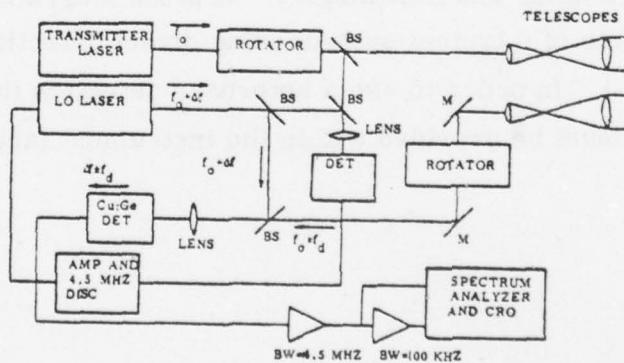


Figure 7.3.1-2. Block Diagram for LWIR Long-Path System Using Single Laser and Heterodyne Detection (adopted from Ref. 258).

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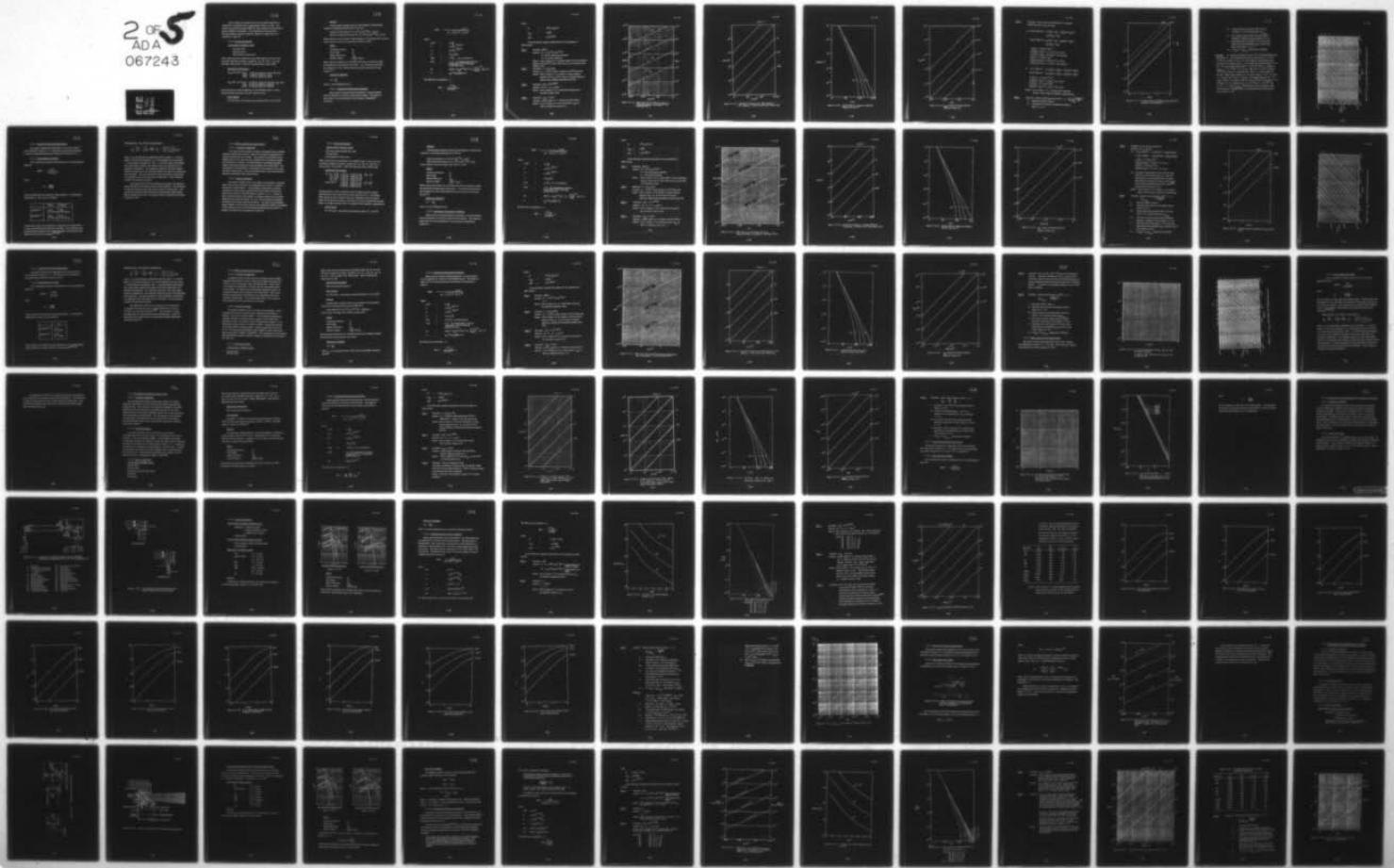
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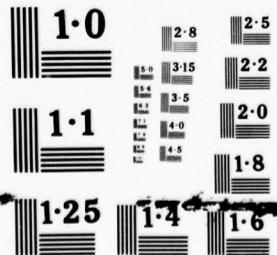
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The hd method is potentially much more sensitive than the dd method and is desirable when a topographical reflector is used. The maximum permissible energy (MPE) for laser systems has been promulgated by DHEW in 21CFR1040. If the regulations of the American National Standards Institute (ANSI) are adopted, the MPE may be increased by a factor 50.

### 7. 3. 1. 3 System Parameters

#### Commercially Available Lasers

$\text{CO}_2$  Gas Laser

$\text{N}_2\text{O}$  Gas Laser

Semiconductor-Diode Laser

Other lasers that have transitions in the LWIR region, but are not commercially available at present, include Ne,  $\text{N}_2$ , Xe, OCS, I,  $\text{O}_2$ , and HF (Refs. 256 and 257). Both CW and pulsed lasers may be used.

#### Operational Wavelengths

$\text{CO}_2$ ( $00^{\circ}1-02^{\circ}0$ ) P(14)	9.504 $\mu\text{m}$ useful for ozone	(Ref. 251)
P(20)	9.552 $\mu\text{m}$ useful for ozone	" "
P(24)	9.586 $\mu\text{m}$ useful for ozone	" "

$\text{CO}_2$ ( $00^{\circ}1-10^{\circ}0$ ) P(14)	10.529 $\mu\text{m}$ useful for ethylene	(Ref. 251)
P(16)	10.549 $\mu\text{m}$ useful for ethylene	" "
P(20)	10.588 $\mu\text{m}$ useful for ethylene	" "

The coincidence of other transitions of the available lasers to ozone and the hydrocarbons have not been reported as yet.

#### Laser Energy

For CW lasers, the maximum permissible power is  $0.1 \text{ W/cm}^2$ .

7. 3. 1. 3b

7. 3. 1. 4a

### Detector

Commercially available detectors with highest D\* and practical risetimes at operating temperatures of 77 K are

Lead-Tin-Telluride ( $D^* \sim 5 \times 10^{10} \text{ cm Hz}^{1/2}/\text{W}$ ,  $t \sim 10 \text{ ns}$ )

Mercury-Cadmium-Telluride ( $D^* \sim 3 \times 10^{10} \text{ cm Hz}^{1/2}/\text{W}$ ,  $t < 1 \text{ ns}$ )

These detectors can be made to peak anywhere in the region from 8-12  $\mu\text{m}$ . Active detector areas can range from 0.0025 to 1  $\text{mm}^2$ .

### Optics

Collecting Aperture  $A_o$

Solid Angle  $\Omega_o$

Optical Efficiency  $\eta_{\text{opt}}$

Detector Optics  $A_d \Omega_d (= A_o \Omega_o)$

These optical parameters are variables that must be chosen to fulfill the operational requirements (see below). For heterodyne detection, the constraint for the coherent aperture must be taken into account ( $A_o \Omega_o \approx \lambda^2$ ).

### Electronic Bandpass

$$\Delta f = \frac{1}{4t_c}$$

where  $t_c$  is the integration time.

### 7. 3. 1. 4 Theoretical Performance Prediction

Based upon the selected system parameters, the performance can be predicted for a detector-noise-limited system. The signal-to-noise ratio for the determination of the pollutant concentration is given by

$$\text{SNR} = \frac{\ln Q^1}{dP \sqrt{(1/P)^2 + (1/P')^2}}$$

where

$$\begin{aligned}
 \ln Q^1 &= \ln \frac{P}{P'} - 2k_1 C R \\
 P &= (G/R^2)e \\
 P' &= (G/R^2)e^{-2k_2 C R} \\
 G &= \eta P_t A_o \Gamma(R) \\
 \Gamma(R) &\approx 1/(\pi \Omega_o) \quad \text{for retroreflector} \\
 \Gamma(R) &= \rho'/\pi \quad \text{for topographical reflector} \\
 &\quad (\text{independent of } R \text{ if reflecting surface fills fov}) \\
 dP &= \text{NEP/F} = (A_d \Delta f)^{1/2} (D^*)^{-1}/F = \left( \frac{A_d}{4t_c} \right)^{1/2} (D^*)^{-1}/F \\
 F &= \eta_Q \lambda^3 / 2\Omega_d \sqrt{A_d B} hc D^*
 \end{aligned}$$

The SNR may be simplified, i. e.,

$$\text{SNR} = \frac{Q P_{\text{eff}}}{\sqrt{2} \text{NEP/F}}$$

where

$$Q = 2 \sum (k_1 - k_2) C_i R$$

$$P_{\text{eff}} = G \xi(R)$$

$$\xi(R) = R^{-2} e^{-2kCR}$$

In the following a stepwise description for the calculation of SNR is given

Step 1: Calculate: NEP/F

Assume:  $D^* = 3 \times 10^{10} \text{ cm Hz}^{1/2} \text{W}^{-1}$

$F \approx 100$  for heterodyne detection

$F = 1$  for direct detection

Result: Plot in Figure 7.3.1-3 shows NEP/F (over an adequate range to cover both  $F=1$  and  $F=100$ ) versus  $A_d$  for different integration times.

Step 2: Calculate:  $G = \eta P_t A_o \Gamma(R)$

Assume:  $P_t = 1 \text{ W}$  for a laser, having a  $10 \text{ cm}^2$  beam area.

Result: Plot in Figure 7.3.1-4 shows  $G$  versus receiver aperture area  $A_o$  for five values of overall efficiency (optical and mechanical shutters) and  $\Gamma(R)$ .

Step 3: Calculate:  $\xi(R) = R^{-2} e^{-2kCR}$

Assume:  $kC = 0, .3, 1, 3 \text{ km}^{-1}$

Result: Plot in Figure 7.3.1-5 shows  $\xi(R)$  versus  $R$  for the above values of  $kC$ .

Step 4: Calculate:  $P_{\text{eff}} = G \xi(R)$

Assume: Useful range of  $R$  between 100 and 1000 m

Result: Plot in Figure 7.3.1-6 which shows  $P_{\text{eff}}$  vs.  $\xi(R)$  for different values of  $G$ .

7.3.1.4d

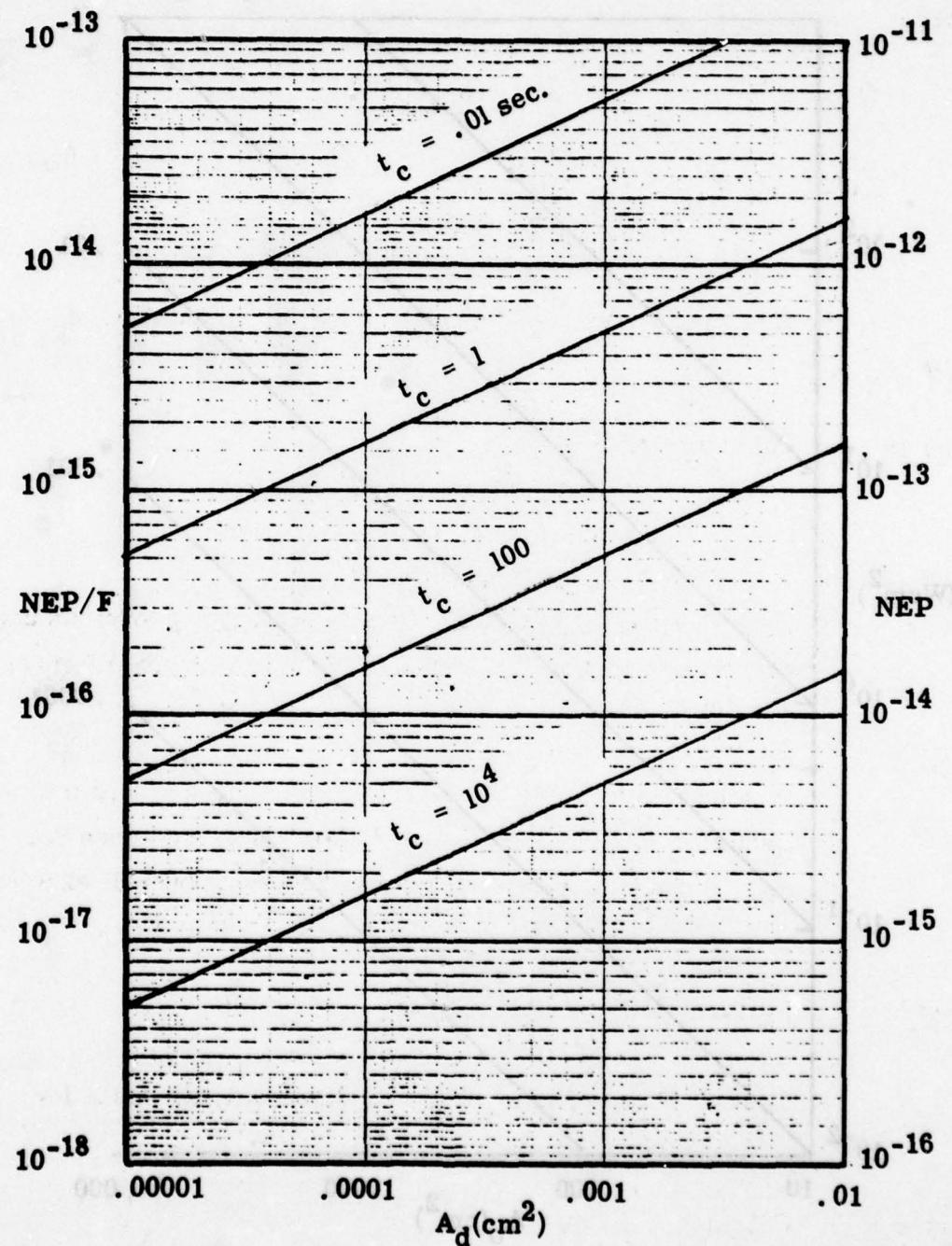


Figure 7.3.1-3. NEP versus  $A_d$  for Different Values of Integration Times, Assuming  $D^* = 3 \times 10^{10} \text{ cmH}^{1/2} \text{W}^{-1}$ .

7.3.1.4e

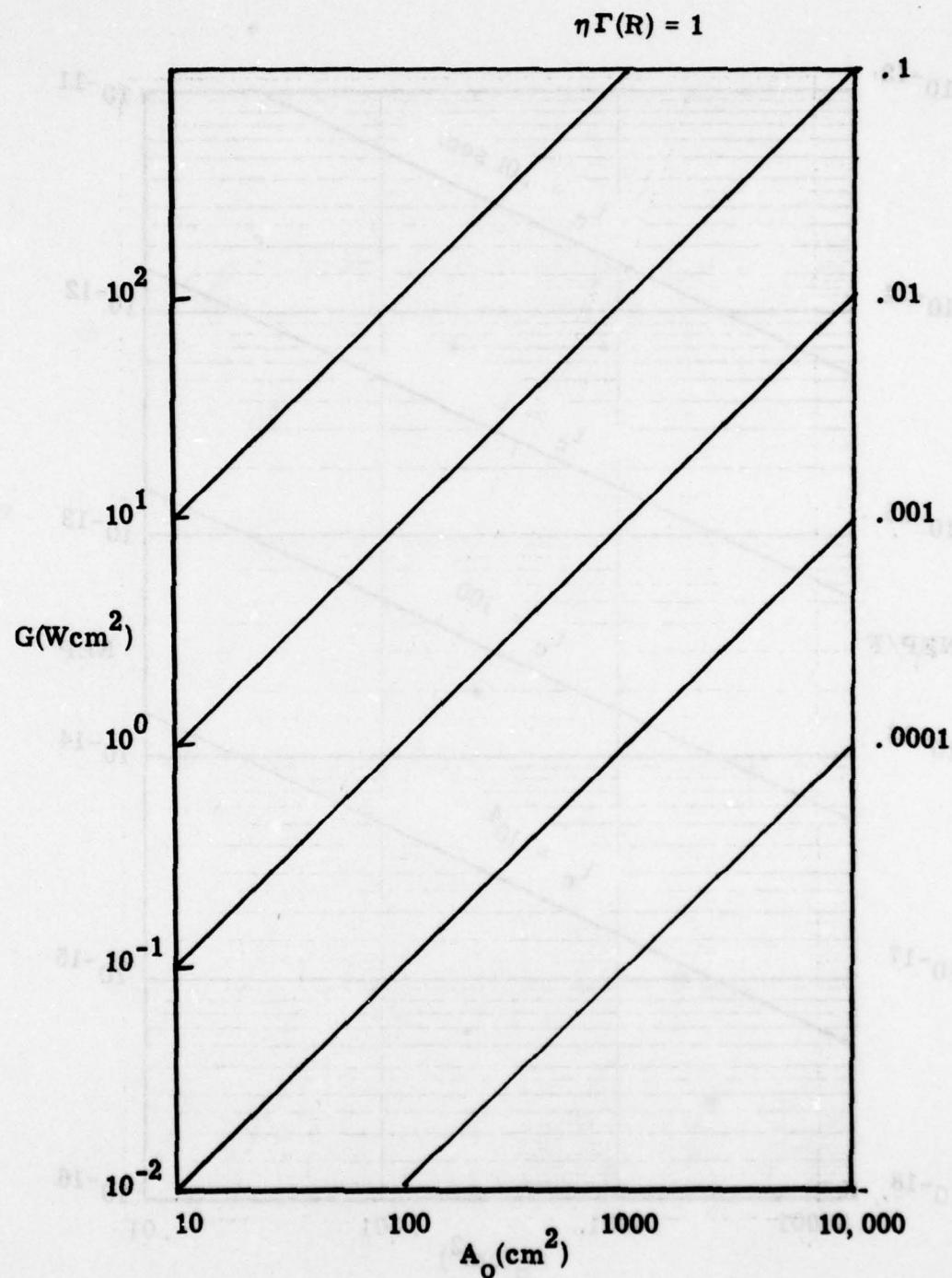


Figure 7.3.1-4. Function  $G$  versus  $A_0$  for Five Values of  $\eta\Gamma$ , using  $P_t = 1 \text{ W}$  for  $10 \text{ cm}^2$  Laser Beam Area.

7. 3. 1. 4f

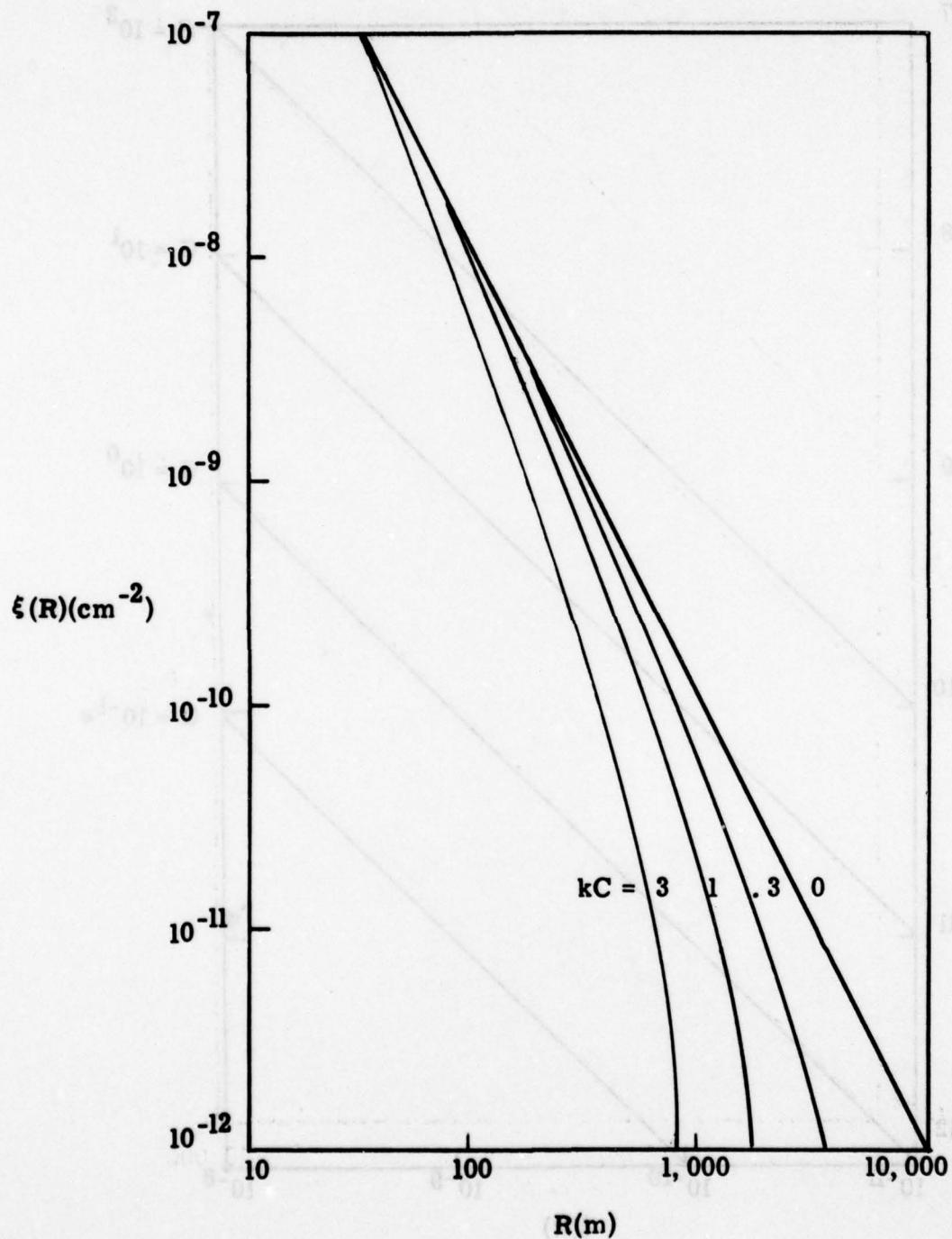


Figure 7. 3. 1-5. Function  $\xi(R)$  vs. Range for Different Values of  $kC$  ( $\text{km}^{-1}$ )

7.3.1.4g

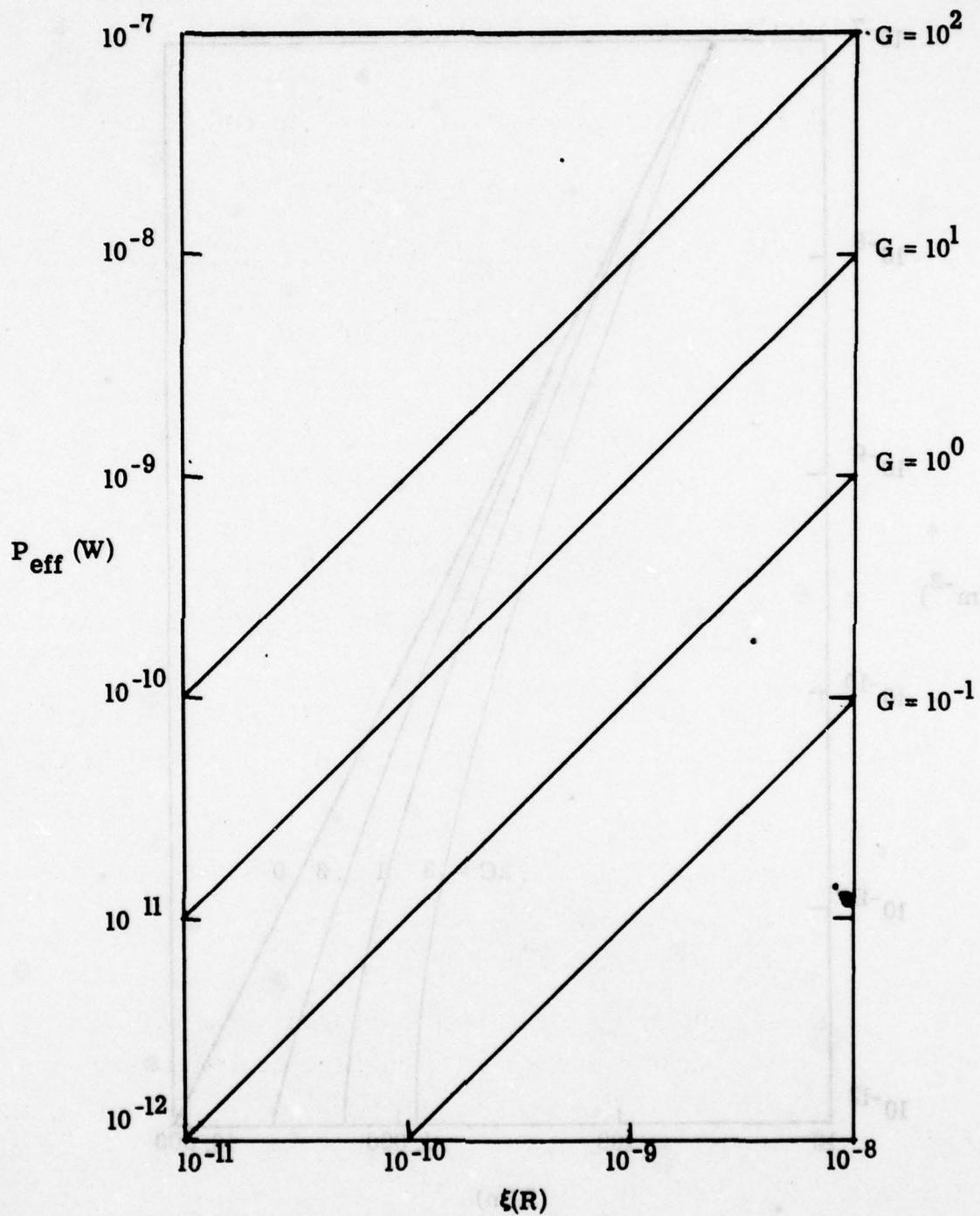


Figure 7.3.1-6  $P_{\text{eff}}$  versus the Function  $\xi(R)$  for Different Values of  $G$

7. 3. 1. 4h

Step 5: Calculate: Q for ozone (a) and ethylene (b), (including interfering species  $\text{CO}_2$  and  $\text{H}_2\text{O}$ )

$$\text{a)} \Sigma k_1(9.504\mu\text{m})C_i = k_1(\text{O}_3)\text{C}(\text{O}_3) + k_1(\text{H}_2\text{O})\text{C}(\text{H}_2\text{O}) + k_1(\text{CO}_2)\text{C}(\text{CO}_2)$$

$$\Sigma k_2(9.586\mu\text{m})C_i = k_2(\text{O}_3)\text{C}(\text{O}_3) + k_2(\text{H}_2\text{O})\text{C}(\text{H}_2\text{O}) + k_2(\text{CO}_2)\text{C}(\text{CO}_2)$$

$$k_1(\text{O}_3) = 1.25 \text{ ppm}^{-1}\text{km}^{-1}$$

$$k_1(\text{H}_2\text{O})\text{C}(\text{H}_2\text{O}) = 0.11 \text{ km}^{-1} \text{ for 10 torr}$$

$$k_1(\text{CO}_2)\text{C}(\text{CO}_2) = 0.123 \text{ km}^{-1} \text{ for 330 ppm}$$

$$k_2(\text{O}_3) = 0.08 \text{ ppm}^{-1}\text{km}^{-1}$$

$$k_2(\text{H}_2\text{O})\text{C}(\text{H}_2\text{O}) = 0.09 \text{ km}^{-1} \text{ for 10 torr}$$

$$k_2(\text{CO}_2)\text{C}(\text{CO}_2) = 0.112 \text{ km}^{-1} \text{ for 330 ppm}$$

$$\text{b)} \quad k_1(10.529\mu\text{m})\text{C} = k_1(\text{C}_2\text{H}_4)\text{C}(\text{C}_2\text{H}_4) + k_1(\text{H}_2\text{O})\text{C}(\text{H}_2\text{O})$$

$$k_2(10.588\mu\text{m})\text{C} = k_2(\text{C}_2\text{H}_4)\text{C}(\text{C}_2\text{H}_4) + k_2(\text{H}_2\text{O})\text{C}(\text{H}_2\text{O})$$

$$k_1(\text{C}_2\text{H}_4) = 2.98 \text{ ppm}^{-1}\text{km}^{-1}$$

$$k_1(\text{H}_2\text{O})\text{C}(\text{H}_2\text{O}) = 0.12 \text{ km}^{-1} \text{ for 10 torr}$$

$$k_2(\text{C}_2\text{H}_4) = 0.15 \text{ ppm}^{-1}\text{km}^{-1}$$

$$k_2(\text{H}_2\text{O})\text{C}(\text{H}_2\text{O}) = 0.11 \text{ km}^{-1} \text{ for 10 torr}$$

Result: Plot in Figure 7.3.1-7 shows Q for ozone and ethylene versus range for different concentrations.

Step 6: Calculate: System Performance for  $\text{SNR} = 1$ , i.e.,  $(P_{\text{eff}})_{\text{min}} = \frac{\sqrt{2} \text{ NEP/F}}{Q}$

i) Determine NEP/F (Step 1)

ii) Calculate Q for desired concentration (Step 5,  
Figure 7.3.1-7)

7.3.1.4i

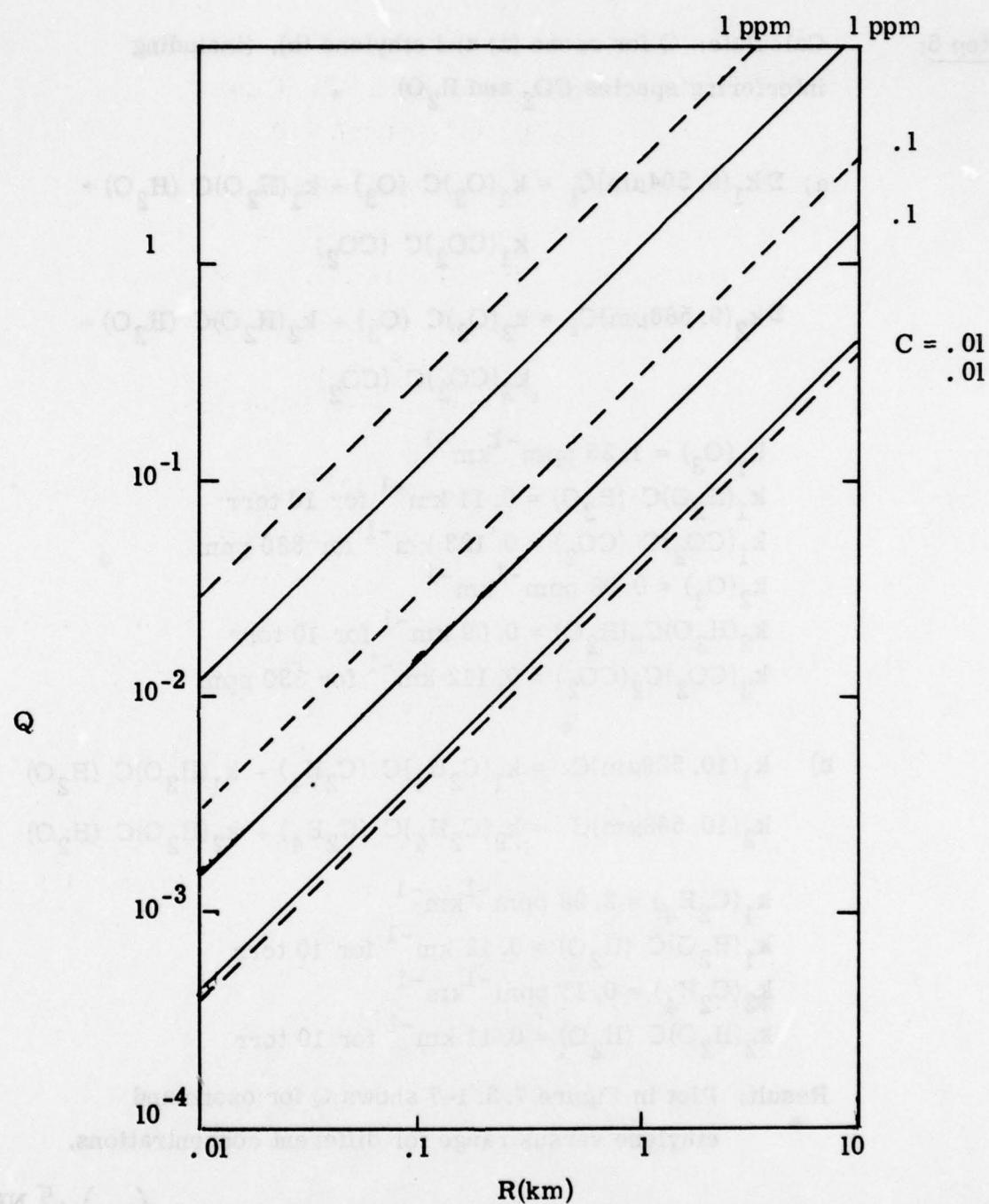


Figure 7.3.1-7. Q versus Range for Different Concentrations of Ozone (-) and Ethylene (----).

7. 3. 1. 4j

- iii) Locate intersection between NEP/F and Q in Figure 7. 3. 1-8 and determine  $(P_{\text{eff}})_{\text{min}}$
- iv) For a given receiver optics area and overall efficiency, determine G from Figure 7. 3. 1-4.
- v) Determine  $\xi(R)$  from Figure 7. 3. 1-5 for given range and kC and establish  $P_{\text{eff}}$  for given G and  $\xi$  from Figure 7. 3. 1-6.
- vi) If  $(P_{\text{eff}}) > (P_{\text{eff}})_{\text{min}}$  experiment is feasible.

Example: (i) Assume the detector area is  $10^{-3} \text{ cm}^2$  and the integration time is 100 sec. The resulting NEP for direct detection ( $F = 1$ ) is  $5 \times 10^{-14} \text{ W}$  from Figure 7. 3. 1-3. (ii) The minimum concentration of  $O_3$  of interest is 0.06 ppm thus  $Q = .1$  at a range of 1 km from Figure 7. 3. 1-7. (iii) The intersection between  $\text{NEP}/F = 5 \times 10^{-14}$  and  $Q = .1$  results in  $(P_{\text{eff}})_{\text{min}} = 7 \times 10^{-13} \text{ W}$ . (iv) For  $A_o = 1000 \text{ cm}^2$ ,  $R = 10^3 \text{ m}$  and  $\Omega_L \approx 10^{-6} \text{ sr}$ , the value for  $\Gamma$  becomes 0.03. With  $\eta = .01$  the product  $\eta\Gamma$  becomes .0003, which results in  $G = 0.3$  from Figure 7. 3. 1-4. (v) Since  $k = 1.25 \text{ ppm}^{-1} \text{ km}^{-1}$  and  $C = 0.06 \text{ ppm}$ , the product becomes .08. At a range of 1000 m, one finds  $\xi(1000 \text{ m}) \approx 9 \times 10^{-11} (\text{cm}^{-2})$  in Figure 7. 3. 1-5. In Figure 7. 3. 1-6, one finds  $P_{\text{eff}} = 3 \times 10^{-11} \text{ W}$  for  $\xi = 9 \times 10^{-11}$  and  $G = 0.3$ . (vi) Since  $(P_{\text{eff}})_{\text{min}} \approx 40$  indicates that for a detector-noise-limited system, .06 ppm of  $O_3$  may be measured within 2.5% accuracy over a range of 1 km.

7. 3. 1. 4k

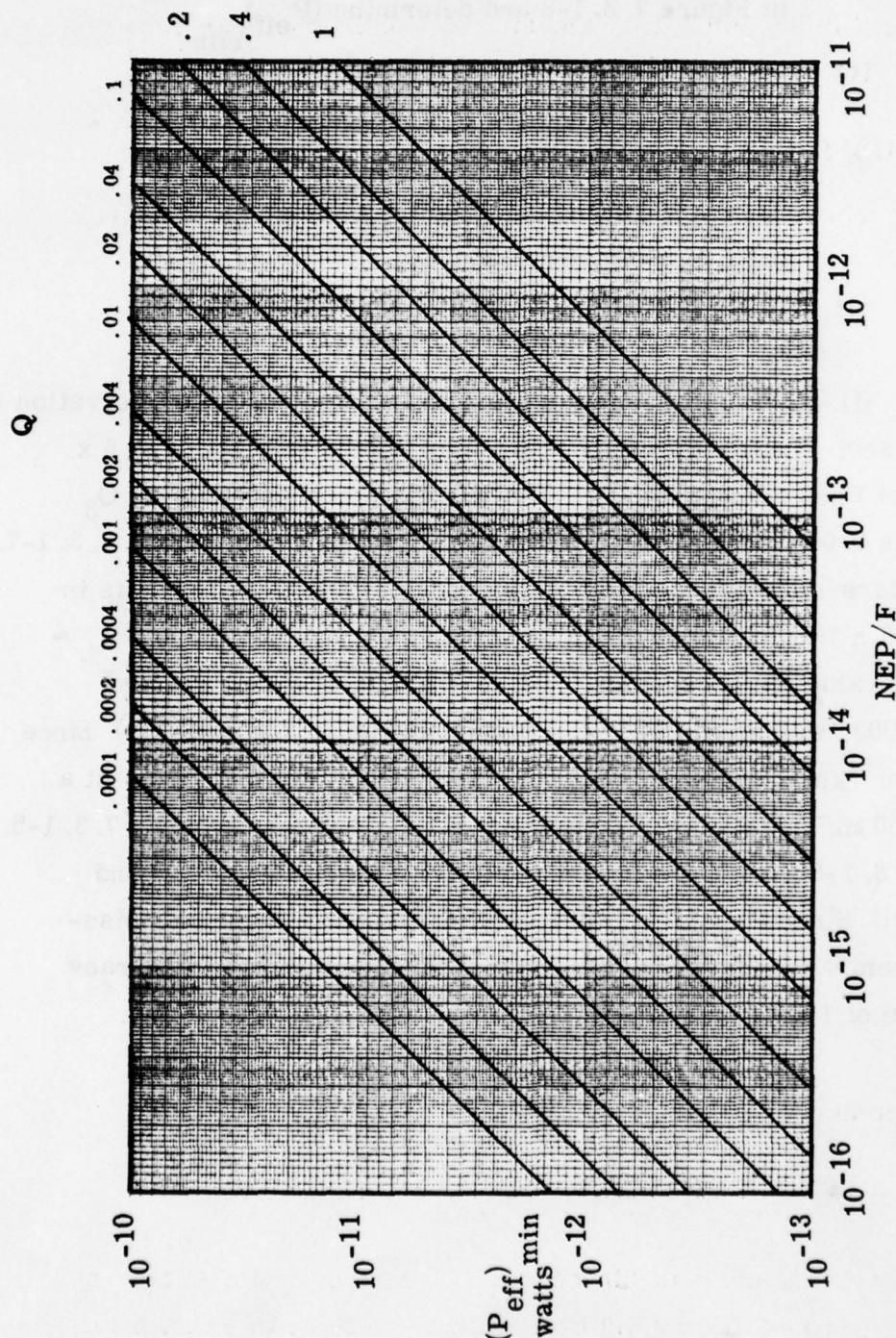


Figure 7.3.1-8.  $P_{eff}$  versus NEP/F for Different Values of  $Q$ .

### 7.3.1.5 Special Performance Requirements

The general requirements applicable to all remote monitors were described in Section 7.1.1, and special requirements applicable to ozone and total hydrocarbons were described in Section 7.2.1.5.

### 7.3.1.6 Data Analysis Procedure

The concentration (in ppm) is determined in a very good approximation by

$$C(\text{ppm}) = \frac{\ln Q}{2(k_1 - k_2) R}$$

where

$$Q = \frac{P(R)}{P'(R)}$$

The two signals are determined from analog signals. The absorption coefficients  $k_1$  and  $k_2$  are as follows:

	Ozone	Ethylene
$k_1 (\text{ppmkm})^{-1}$	1.25 @ 9.504 $\mu\text{m}$	2.98 @ 10.529 $\mu\text{m}$
$k_2 (\text{ppmkm})^{-1}$	0.08 @ 9.586 $\mu\text{m}$	0.15 @ 10.588 $\mu\text{m}$

As previously noted, the coincidence of transitions of available lasers to other hydrocarbons has not yet been reported. Since turbulence can introduce large variations in the received signals, the derivative/ratio signal method has been developed (242, 243).

Mathematically, this method is expressed as

$$\frac{1}{P_r} \frac{d P_r}{d\omega} = \frac{\delta P_r}{\delta k(\omega)} \frac{\delta k(\omega)}{\delta \omega} \frac{1}{P_r} = \frac{2 k_0 l (\omega - \omega_0) c}{\gamma^2 [1 + (\omega - \omega_0)^2 / \gamma^2]^2}$$

where  $k_0$  is the absorption coefficient at the line center,  $l$  is the distance,  $\omega$  is the laser frequency,  $\omega_0$  is the frequency at the line center,  $c$  is the pollutant concentration, and  $\gamma$  is the half-width at half-height. For a given laser frequency the signal is directly proportional to the pollutant concentration. For maximum sensitivity, the ratioed signal should be evaluated at a laser frequency where the slope of the absorption line is greatest. The only exception is when the pollutant concentration is so high that most of the laser power is absorbed. In such instances a weaker line should be selected.

The signal  $[(d P_r / d\omega) / P_r]$  as a function of pollutant concentration can be obtained from laboratory and/or field calibration. The calibration is made by using a gas cell with a known amount of pollutant gas. This can be done during the actual field test by observing the signal change after inserting the gas cell. An example of such a calibration was shown in Figure 2. 5-39.

7.3.2 MWIR Long-Path with Laser Source

7.3.2.1 Principle of Operation

The measurement principle of medium wavelength infrared (MWIR) long-path transmission is used to obtain line-averaged concentrations of carbon monoxide and nitrous oxide. Laser beams at two different wavelengths in the 4.8-5.4  $\mu\text{m}$  region are emitted and the transmitted signals are recorded by a receiver. By differencing the wavelength-dependent signals, the average absorption of the pollutants can be determined. The concentration of the pollutant is proportional to the logarithm of the monochromatic transmission. The proportionality factor is the monochromatic absorption coefficient which must be known.

7.3.2.2 System Description

The system consists of one or two lasers as transmitter, collecting optics which may be common to the transmitter and receiver, a detector, electronics and data display. A block diagram indicating the essential elements of a typical system using direct detection (dd) is basically the same as was shown for the LWIR system in Figure 7.3.1-1. In order to use a heterodyn detection (hd) system, a frequency shift must be provided within the instrument (see Figure 7.2.1-2). The hd method is potentially somewhat more sensitive than the dd method. The maximum permissible energy (MPE) for laser systems has been promulgated by DHEW in 21CFR1040. If the regulations of the American National Standards Institute (ANSI) are adopted, the MPE may be increased by a factor 50.

### 7.3.2.3a

#### 7.3.2.3 System Parameters

##### Commercially Available Lasers

Dbl CO<sub>2</sub> Pumped Spinflip Gas Laser

CO Gas Laser

Semiconductor-Diode Laser

Other lasers that have transitions in the MWIR region, but are not commercially available at present, include DCl, Ar, CN, Kr, H<sub>2</sub>O, Xe, I, and O<sub>2</sub> (Refs. 256 and 257). Both CW and pulsed lasers may be used.

##### Operational Wavelengths

CO, 6-5, P(20)	5.176 μm	useful for NO	(Ref. 251)
7-6, P(13)	5.166 μm	useful for NO	" "
7-6, P(15)	5.187 μm	useful for NO	" "
9-8, P(9)	5.262 μm	useful for NO	" "
Diode Laser	4.755 μm	useful for CO	(Ref. 242)
	4.746 μm	useful for CO	" "
	4.702 μm	useful for CO	" "

The coincidence of other transitions of the available lasers to carbon monoxide and nitrous oxide have not been reported as yet. The CO gas laser cannot be used to observe CO in the atmosphere since the lowest observed vibrational transition in the laser is in the 5-4 band [P(18) and up], which is too high an energy level to be populated at atmospheric temperatures.

##### Laser Energy

For CW lasers, the maximum permissible power is 0.1 W/cm<sup>2</sup>.

Detector

Commercially available detectors with highest  $D^*$  and practical risetimes at operating temperatures of 77K are

Indium-Antimonide ( $D^* \sim 10^{11} \text{ cm Hz}^{1/2}/\text{W}$ ,  $t < 1\mu\text{s}$ )

Gold-doped Germanium ( $D^* \sim 2 \times 10^{10} \text{ cm Hz}^{1/2}/\text{W}$ ,  $t \sim 1\mu\text{s}$ )

Active detector areas can range from 0.008 to 1 mm<sup>2</sup>.

Optics

Collecting Aperture  $A_o$

Solid Angle  $\Omega_o$

Optical Efficiency  $\eta_{opt}$

Detector Optics  $A_d \Omega_d (= A_o \Omega_o)$

These optical parameters are variables that must be chosen to fulfill the operational requirements (see below). For heterodyne detection, the constraint for the coherent aperture must be taken into account ( $A_o \Omega_o \approx \lambda^2$ ).

Electronic Bandpass

$$\Delta f = \frac{1}{4 t_c}$$

where  $t_c$  is the integration time.

7.3.2.4 Theoretical Performance Prediction

Based upon the selected system parameters, the performance can be predicted for a detector-noise-limited system. The signal-to-noise ratio for the determination of the pollutant concentration is given by

$$\text{SNR} = \frac{\ln Q^1}{dP \sqrt{(1/P)^2 + (1/P')^2}}$$

where

$$\begin{aligned}
 \ln Q^1 &= \ln \frac{P}{P'} \\
 P &= (G/R^2)e^{-2k_1 C R} \\
 P' &= (G/R^2)e^{-2k_2 C R} \\
 G &= \eta P_t A_o \Gamma(R) \\
 \Gamma(R) &\approx 1/(\pi \Omega_L) \text{ for retroreflector} \\
 \Gamma(R) &= \rho'/\pi \text{ for topographical reflector} \\
 &\text{(independent of } R \text{ if reflecting surface fills fov)} \\
 dP &= \text{NEP/F} = (A_d \Delta f)^{1/2} (D^*)^{-1}/F = \left( \frac{A_d}{4t_c} \right)^{1/2} (D^*)^{-1}/F \\
 F &= \pi Q^1 \lambda^3 / 2 \Omega_d \sqrt{A_d B} hc D^*
 \end{aligned}$$

The SNR may be simplified, i. e.,

$$\text{SNR} = \frac{Q P_{\text{eff}}}{\sqrt{2} \text{NEP/F}}$$

where

$$Q = 2\sum (k_1 - k_2) i C_i R$$

$$P_{\text{eff}} = G \xi(R)$$

$$\xi(R) = R^{-2} e^{-2kCR}$$

In the following a stepwise description for the calculation of SNR is given

Step 1: Calculate:  $\text{NEP}/F$

$$\text{Assume: } D^* = 10^{11} \text{ cm Hz}^{1/2} \text{ W}^{-1}$$

$F = 10$  for heterodyne detection

$F = 1$  for direct detection

Result: Plot in Figure 7.2.2-1 shows  $\text{NEP}/F$  (over an adequate range to cover both  $F=1$  and  $F=100$ ) versus  $A_d$  for different integration times

Step 2: Calculate:  $G = \eta P_t A_o \Gamma(R)$

$$\text{Assume: } P_t = 1 \text{ W for a laser having a } 10 \text{ cm}^2 \text{ beam area}$$

Result: Plot in Figure 7.3.2-2 shows  $G$  versus receiver aperture area  $A_o$  for five values of overall efficiency (optical and mechanical shutters) and  $\Gamma(R)$

Step 3: Calculate:  $\xi(R) = R^{-2} e^{-2kCR}$

$$\text{Assume: } kC = 0, .3, 1, 3 \text{ km}^{-1}$$

Result: Plot in Figure 7.3.2-3 shows  $\xi(R)$  versus  $R$  for the above values of  $kC$

Step 4: Calculate:  $P_{\text{eff}} = G \xi(R)$

Assume: Useful range of  $R$  between 100 and 1000 m

Result: Plot in Figure 7.3.2-4 which shows  $P_{\text{eff}}$  vs.  $\xi(R)$  for different values of  $G$ .

7. 3. 2. 4d

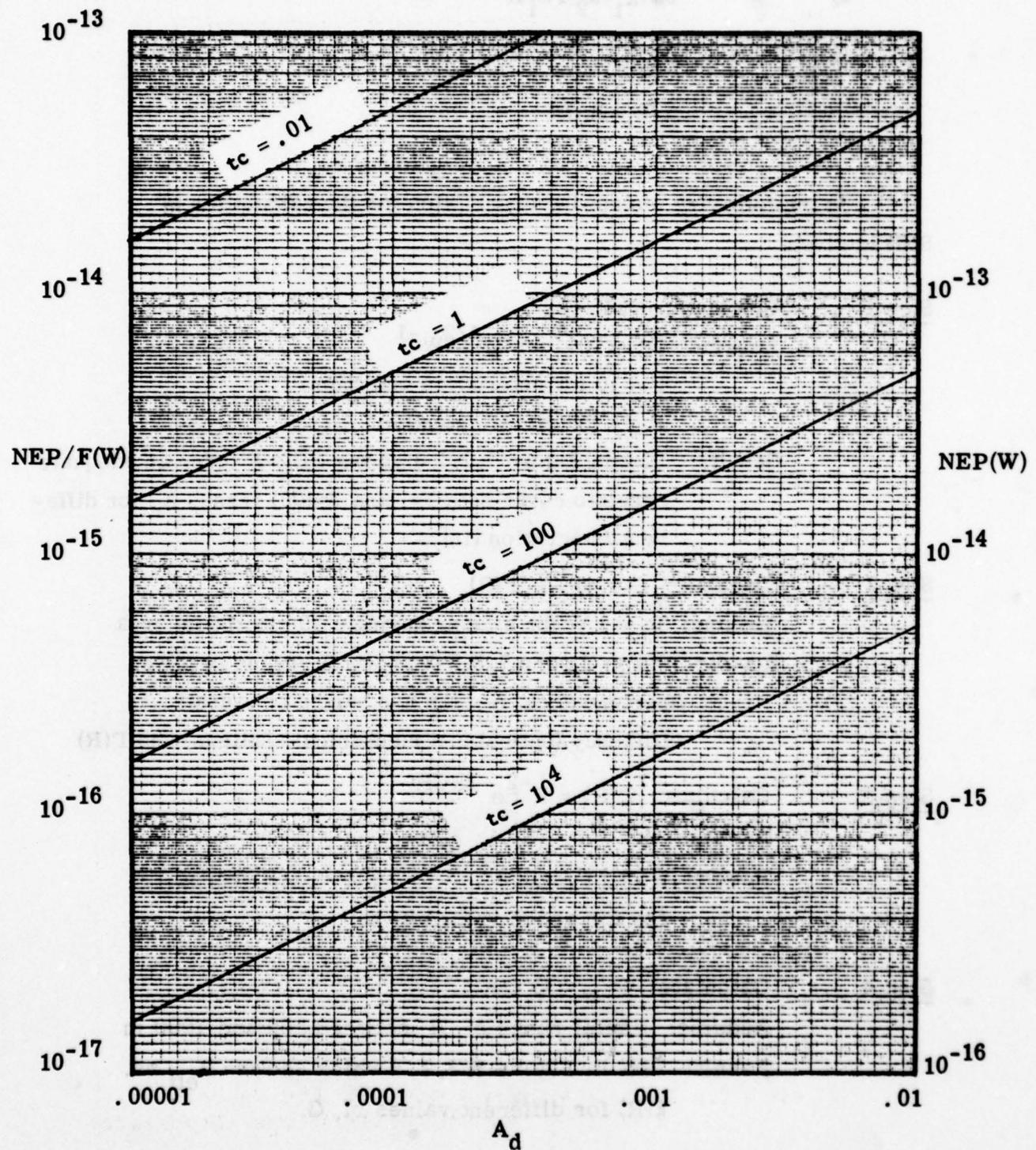


Figure 7. 3. 2-1. NEP versus  $A_d$  for Different Values of Integration Time, Assuming  $D^* = 10^{11} \text{ cmH}^{1/2} \text{W}^{-1}$ .

7.3.2.4e

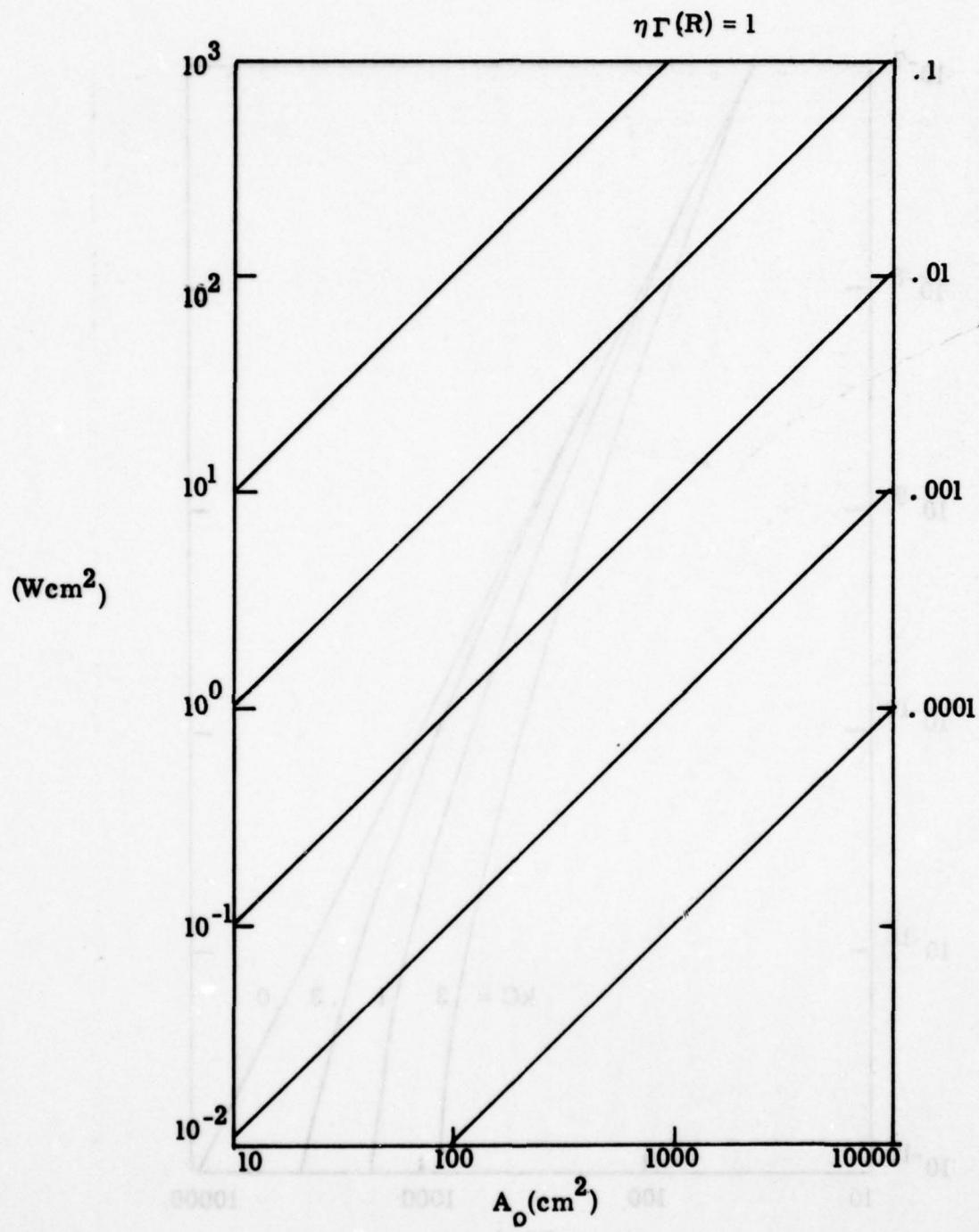


Figure 7.3.2-2. Function G versus  $A_0$  for Five Values of  $\eta \Gamma$  using  $P_t = 1$  W for  $10 cm^2$  Laser Beam Area.

7.3.2.4f

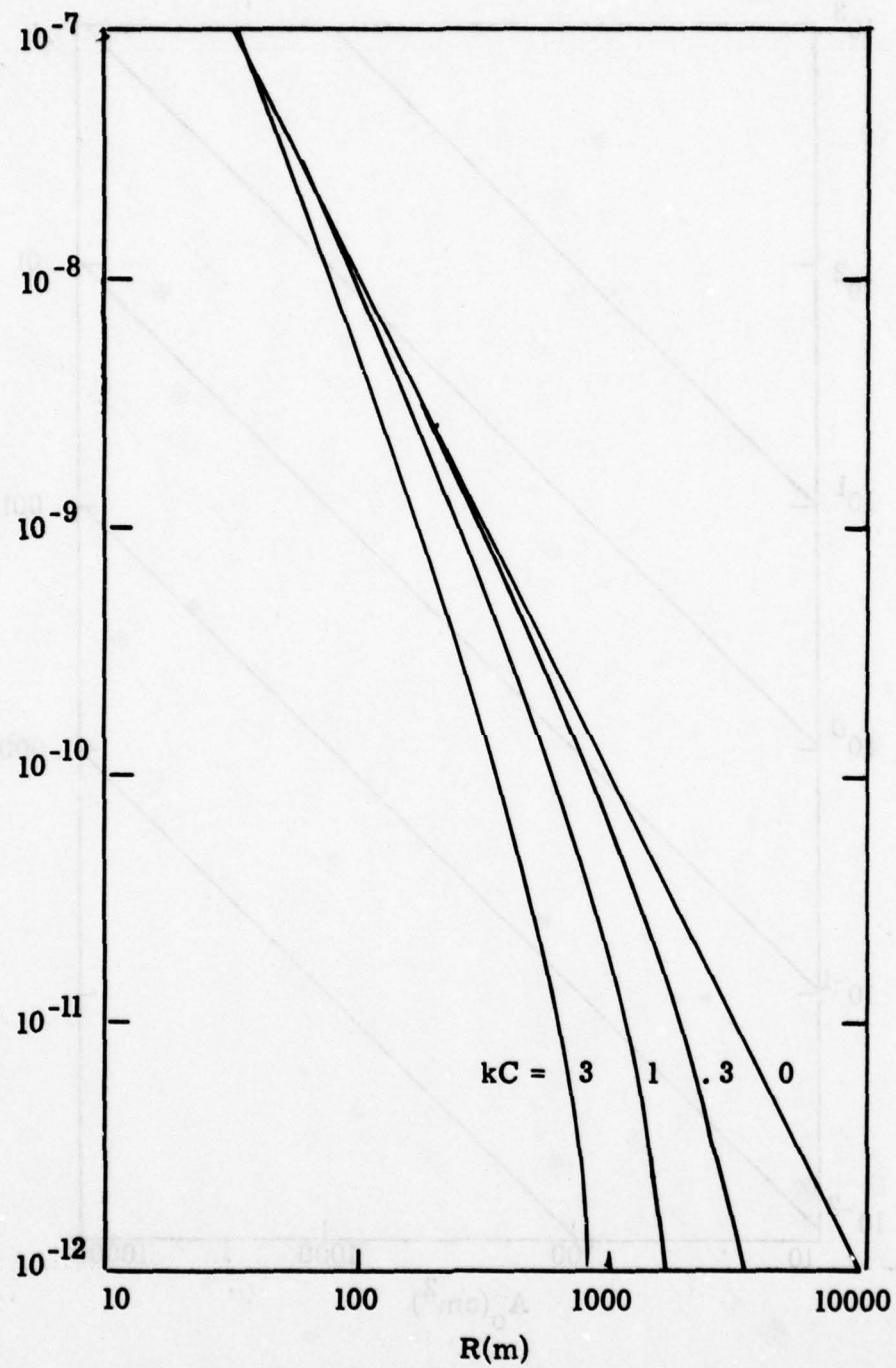
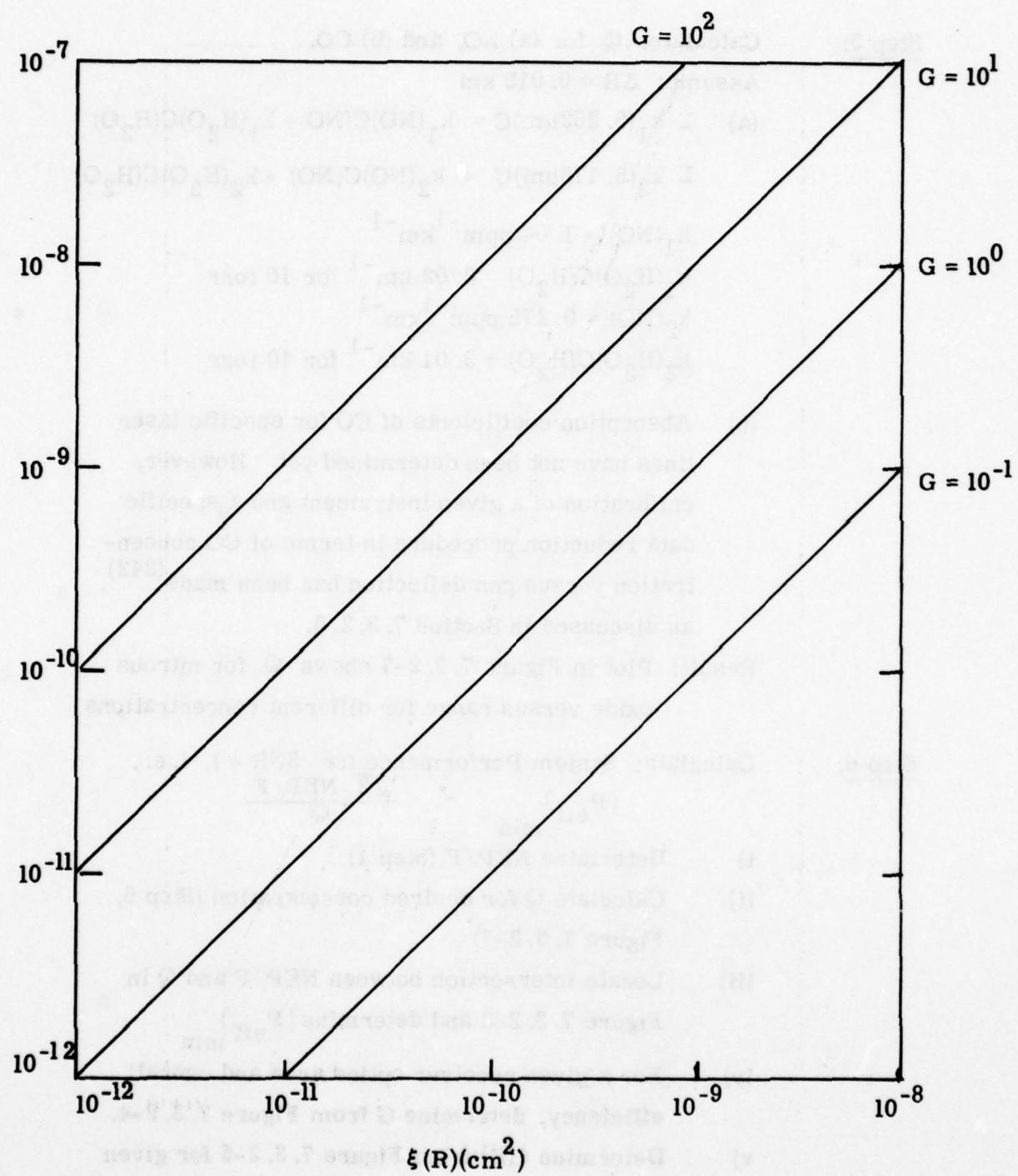


Figure 7.3.2-3. Function  $\xi(R)$  vs. Range for Different Values of  $kC$  ( $\text{km}^{-1}$ ).

7.3.2.4g



**Figure 7.3.2-4.**  $P_{\text{eff}}$  versus the Function  $\xi(R)$  for Different Values of  $G$ .

Step 5: Calculate: Q for (a) NO, and (b) CO.

Assume:  $\Delta R = 0.015 \text{ km}$

$$(a) \Sigma k_1(5.262\mu\text{m})C = k_1(\text{NO})C(\text{NO} + k_1(\text{H}_2\text{O})C(\text{H}_2\text{O}))$$

$$\Sigma k_2(5.176\mu\text{m})C = k_2(\text{NO})C(\text{NO} + k_2(\text{H}_2\text{O})C(\text{H}_2\text{O}))$$

$$k_1(\text{NO}) = 1.04 \text{ ppm}^{-1}\text{km}^{-1}$$

$$k_1(\text{H}_2\text{O})C(\text{H}_2\text{O}) = 2.02 \text{ km}^{-1} \text{ for 10 torr}$$

$$k_2(\text{NO}) = 0.275 \text{ ppm}^{-1}\text{km}^{-1}$$

$$k_2(\text{H}_2\text{O})C(\text{H}_2\text{O}) = 2.01 \text{ km}^{-1} \text{ for 10 torr}$$

- (b) Absorption coefficients of CO for specific laser lines have not been determined yet. However, calibration of a given instrument and a specific data reduction procedure in terms of CO concentration versus pen deflection has been made<sup>(242)</sup>, as discussed in Section 7. 3. 2. 6.

Result: Plot in Figure 7. 3. 2-7 shows Q for nitrous oxide versus range for different concentrations.

Step 6: Calculate: System Performance for SNR = 1, i. e.,

$$(P_{\text{eff}})_{\text{min}} = \frac{\sqrt{2} \text{ NEP/F}}{Q}$$

- i) Determine NEP/F (Step 1)
- ii) Calculate Q for desired concentration (Step 5, Figure 7. 3. 2-7)
- iii) Locate intersection between NEP/F and Q in Figure 7. 3. 2-8 and determine  $(P_{\text{eff}})_{\text{min}}$
- iv) For a given receiver optics area and overall efficiency, determine G from Figure 7. 3. 2-4.
- v) Determine  $\xi(R)$  from Figure 7. 3. 2-5 for given range and kC and establish  $P_{\text{eff}}$  for given G and  $\xi$  from Figure 7. 3. 2-6.
- vi) If  $(P_{\text{eff}}) > (P_{\text{eff}})_{\text{min}}$  experiment is feasible.

7.3.2.4i

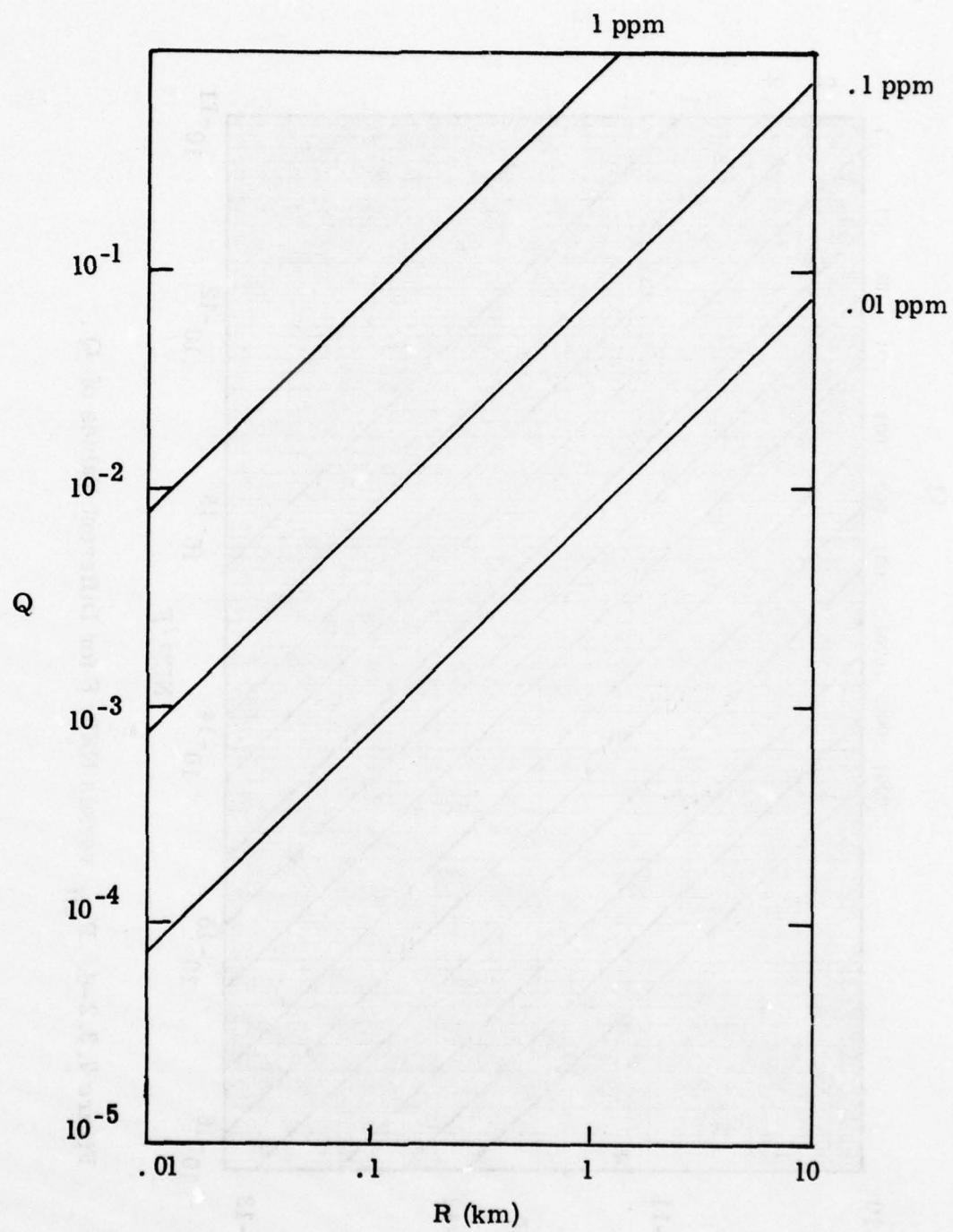


Figure 7.3.2-5.  $Q$  versus Range for Different Concentrations of NO

### 7. 3. 2. 4j

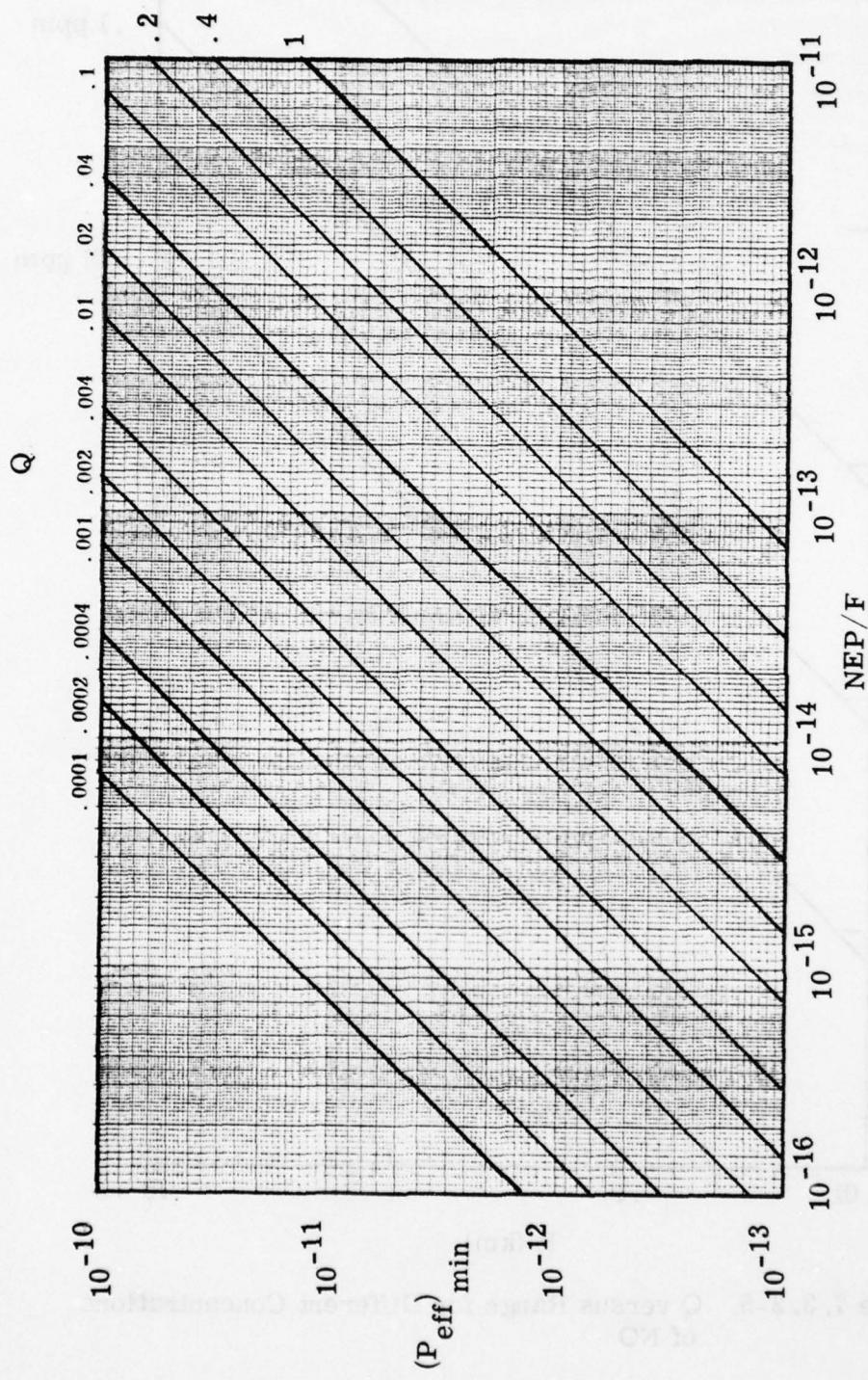


Figure 7.3.2-6.  $P_{eff}$  versus NEP/F for Different Values of Q.

### 7.3.2.5 Special Performance Requirements

The general requirements applicable to all remote monitors were described in Section 7.1.1. For NO<sub>x</sub> and CO, the special requirements were described in Section 7.2.2.5.

### 7.3.2.6 Data Analysis Procedure

The concentration (in ppm) is determined in a very good approximation by

$$C(\text{ppm}) = \frac{\ln Q}{2(k_1 - k_2)}$$

where

$$Q = \frac{P(R)}{P'(R)}$$

The two signals are determined from analog signals. The absorption coefficients  $k_1$  and  $k_2$  are as follows:

	NO
$k_1(\text{ppmkm})^{-1}$	1.04 @ 5.262μm
$k_2(\text{ppmkm})^{-1}$	0.275 @ 5.176μm

Since turbulence can introduce large variations in the received signals, the derivative/ratio signal method has been developed<sup>(242, 243)</sup>

### 7. 3. 2. 6b

Mathematically, this method is expressed as

$$\frac{1}{P_r} \frac{d P_r}{d\omega} = \frac{\delta P_r}{\delta k(\omega)} \frac{\delta k(\omega)}{\delta \omega} \frac{1}{P_r} = \frac{2 k_o l (\omega - \omega_o) c}{\gamma^2 [1 + (\omega - \omega_o)^2 / \gamma^2]^2}$$

where  $k_o$  is the absorption coefficient at the line center,  $l$  is the distance,  $\omega$  is the laser frequency,  $\omega_o$  is the frequency at the line center,  $c$  is the pollutant concentration, and  $\gamma$  is the half-width at half-height. For a given laser frequency the signal is directly proportional to the pollutant concentration. For maximum sensitivity, the ratioed signal should be evaluated at a laser frequency where the slope of the absorption line is greatest. The only exception is when the pollutant concentration is so high that most of the laser power is absorbed. In such instances a weaker line should be selected.

The signal  $[(d P_r/d\omega)/P_r]$  as a function of CO concentration is obtained from laboratory and/or field calibration for a given instrument in terms of pen deflection<sup>(242)</sup>. The calibration is made by using a gas cell with a known amount of pollutant gas. This was done during the actual field test by observing the signal change after inserting the gas cell.

### 7.3.3 SWIR Long-Path with Laser Source

#### 7.3.3.1 Principle of Operations

The measurement principle of short wavelength infrared (SWIR) long-path transmission is used to obtain line-averaged concentrations in the  $2.5\text{-}4 \mu\text{m}$  region ( $\text{NO}_x$ ,  $\text{SO}_2$ ) and hydrocarbons. Laser beams at two different wavelengths are emitted and the transmitted signals are recorded. By differencing the wavelength-dependent signals, the average absorption of the pollutants can be determined. The concentration of the pollutant is proportional to the logarithm of the monochromatic transmission. The proportionality factor is the monochromatic absorption coefficient which must be known.

#### 7.3.3.2 System Description

The system consists of one or two lasers as transmitter, collecting optics which may be common to the transmitter and receiver, a detector, electronics and data display. A block diagram indicating the essential elements of a typical system using direct direction (dd) is basically the same as was shown for the LWIR system in Figure 7.3.3-1. Heterodyne detection (hd) is not useful for SWIR. It should be noted that no prototype SWIR-Long-path system, using two lasers has been tested as yet. The maximum permissible energy (MPE) for laser systems has been promulgated by DHEW in 21CFR1040. If the regulations of the American National Standards Institute (ANSI) are adopted, the MPE may be increased by a factor 50.

#### 7.3.3.3 System Parameters

##### Commercially Available Lasers

HF Gas Laser  
DF Gas Laser

### 7. 3. 3. 3b

Other lasers that have transitions in the SWIR region, but are not commercially available at present, include Kr, Ne, Ar, I, Xe, Br, O<sub>2</sub>, Cl, Cs, N<sub>2</sub>, C, HCl and HBr (Refs. 256 and 257). Both CW and pulsed lasers may be used.

#### Operational Wavelengths

Have not been determined yet.

#### Laser Energy

For CW lasers, the maximum permissible power is 0.1 W/cm<sup>2</sup>.

#### Detector

Commercially available detectors with highest D\* and practical risetimes at operating temperatures of 200 K are

Lead-Sulfide \*D\*~3 x 10<sup>11</sup> cm Hz<sup>1/2</sup>/W, t~300  $\mu$ sec)

Active areas can range from 0.0001 to several mm<sup>2</sup>.

#### Optics

Collecting Aperture A<sub>o</sub>

Solid Angle  $\Omega_o$

Optical Efficiency  $\eta_{opt}$

Detector Optics A<sub>d</sub>  $\Omega_d$  (=A<sub>o</sub>  $\Omega_o$ )

These optical parameters are variables that must be chosen to fulfill the operational requirements (see below).

#### Electronic Bandpass

$$\Delta f = \frac{1}{4t_c}$$

where t<sub>c</sub> is the integration time, which may be increased to optimize the SNR.

### 7. 3. 3. 4 Theoretical Performance Prediction

Based upon the selected system parameters, the performance can be predicted for a detector-noise-limited system. The signal-to-noise ratio for the determination of the pollutant concentration is given by

$$\text{SNR} = \frac{\ln Q^1}{dP \sqrt{(1/P)^2 + (1/P')^2}}$$

where

$\ln Q^1$	=	$\ln \frac{P}{P'} e^{-2k_1 C R}$
$P$	=	$(G/R^2)e^{-2k_1 C R}$
$P'$	=	$(G/R^2)e^{-2k_2 C R}$
$G$	=	$\eta P_t A_o \Gamma(R)$
$\Gamma(R)$	$\approx$	$1/(\pi \Omega_o)$ for retroreflector
$\Gamma(R)$	=	$\rho'/\pi$ for topographical reflector (independent of R if reflecting surface fills fov)
$dP$	=	$\text{NEP}/F = (A_d \Delta f)^{1/2} (D^*)^{-1}/F = \left( \frac{A_d}{4t_c} \right)^{1/2} (D^*)^{-1}/F$
$F$	=	$\eta_Q \lambda^3 / 2 \Omega_d \sqrt{A_d B} hc D^*$

The SNR may be simplified, i. e.,

$$\text{SNR} = \frac{Q P_{\text{eff}}}{\sqrt{2} \text{NEP}/F}$$

where

$$Q = 2 \sum (k_1 - k_2) C_i R$$

$$P_{\text{eff}} = G \xi(R)$$

$$\xi(R) = R^{-2} e^{-2kCR}$$

In the following a stepwise description for the calculation of SNR is given

Step 1: Calculate: NEP/F

$$\text{Assume: } D^* = 3 \times 10^{11} \text{ cm Hz}^{1/2} \text{ W}^{-1}$$

$$F = 1$$

Result: Plot in Figure 7. 3. 3-1 shows NEP versus  $A_d$  for different integration times.

Step 2: Calculate:  $G = \eta P_t A_o \Gamma(R)$

$$\text{Assume: } P_t = 1 \text{ W for a laser having a } 10 \text{ cm}^2 \text{ beam area.}$$

Result: Plot in Figure 7. 3. 3-2 shows G versus receiver aperture area  $A_o$  for five values of overall efficiency (optical and mechanical shutters) and  $\Gamma(R)$ .

Step 3: Calculate:  $\xi(R) = R^{-2} e^{-2kCR}$

$$\text{Assume: } kC = 0, .3, 1, 3 \text{ km}^{-1}$$

Result: Plot in Figure 7. 3. 3-3 shows  $\xi(R)$  versus R for the above values of  $kC$

Step 4: Calculate:  $P_{\text{eff}} = G \xi(R)$

Assume: Useful range of R between 100 and 1000 m

Result: Plot in Figure 7. 3. 3-4 which shows  $P_{\text{eff}}$  vs.  $\xi(R)$  for different values of G.

7. 3. 3. 4c

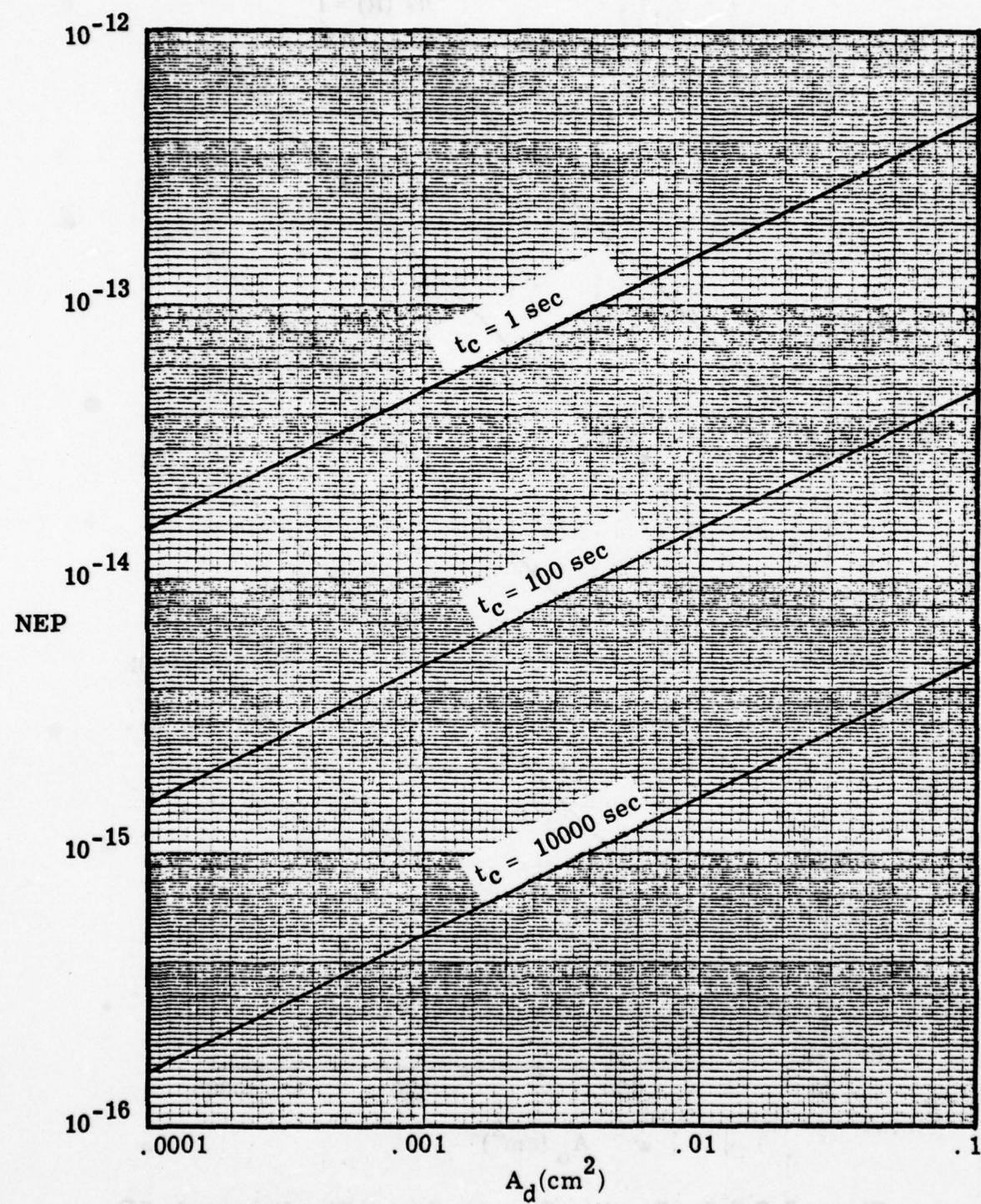


Figure 7.3.3-1. NEP versus  $A_d$  for Different Values of Integration Times Assuming  $D^* = 3 \times 10^{11} \text{ cm H}^{1/2} \text{W}^{-1}$ .

7.3.3.4d

$$\eta \Gamma(R) = 1$$

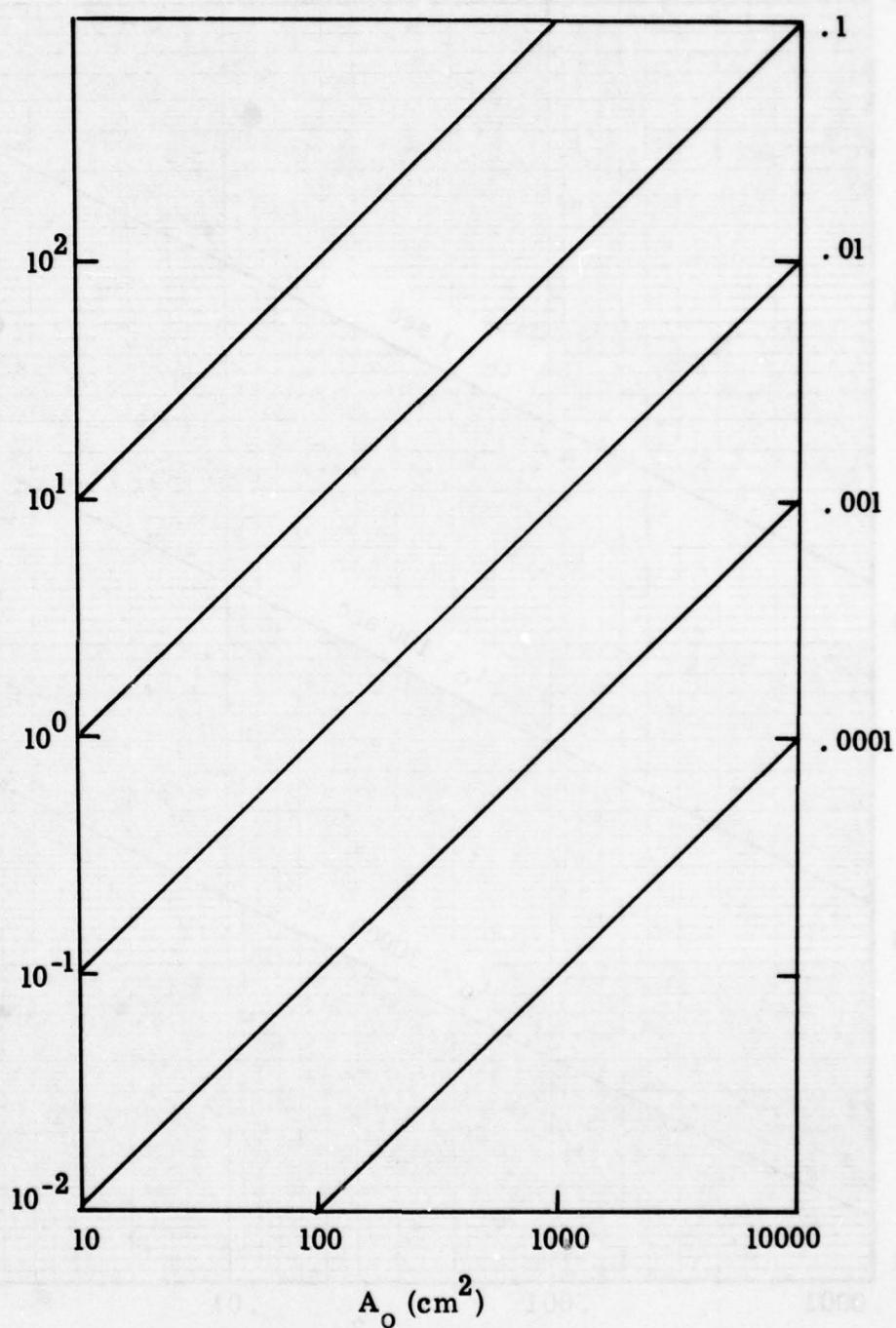


Figure 7.3.3-2. Function  $G$  versus  $A_0$  for Five Values of  $\eta \Gamma$ , Using  $P_r = 1$  for  $10 \text{ cm}^2$  Laser Beam Area.

7.3.3.4e

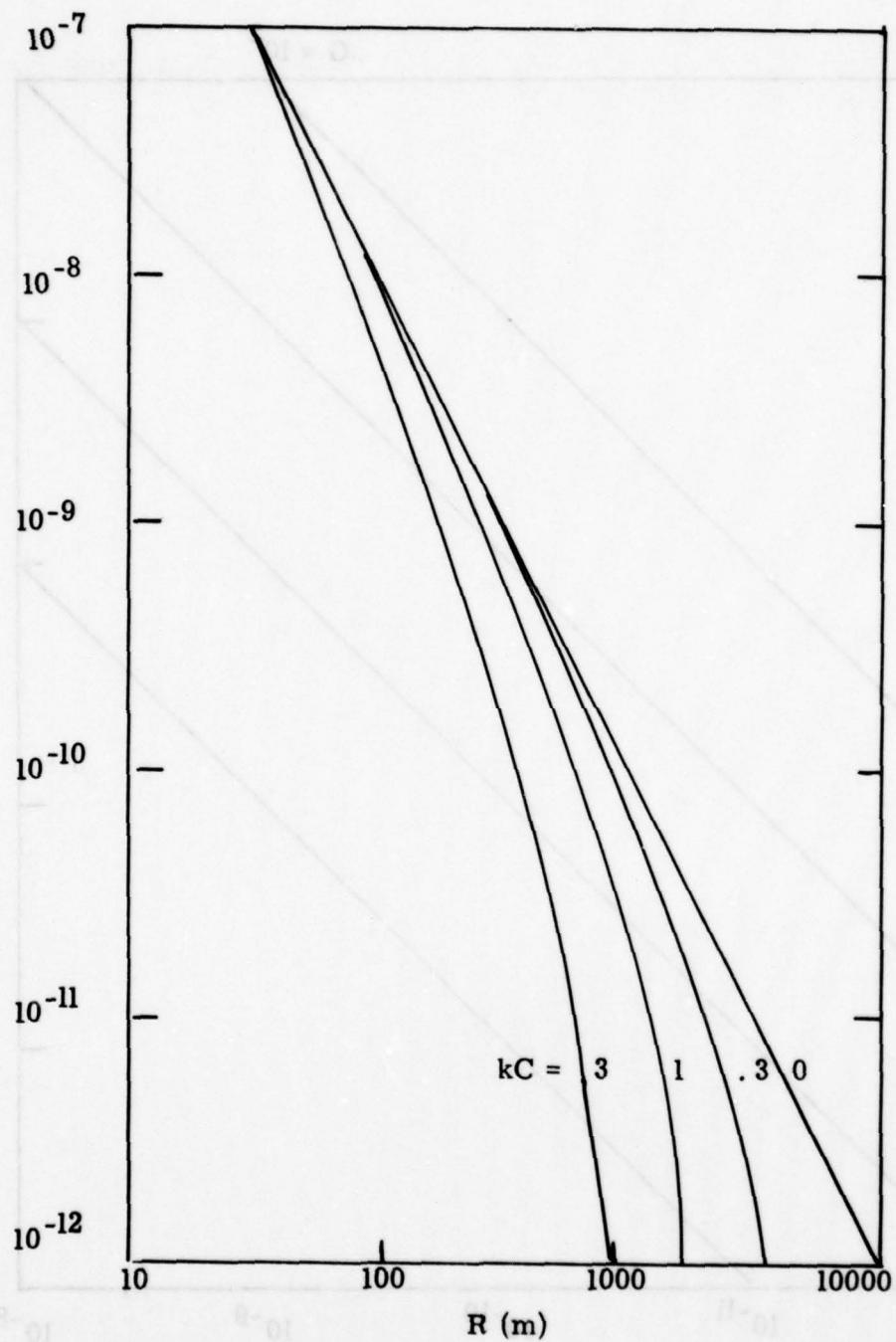


Figure 7.3.3.-3. Function  $\xi(R)$  versus Range for Different Values of  $kC$  ( $\text{km}^{-1}$ )

7. 3. 3. 4f

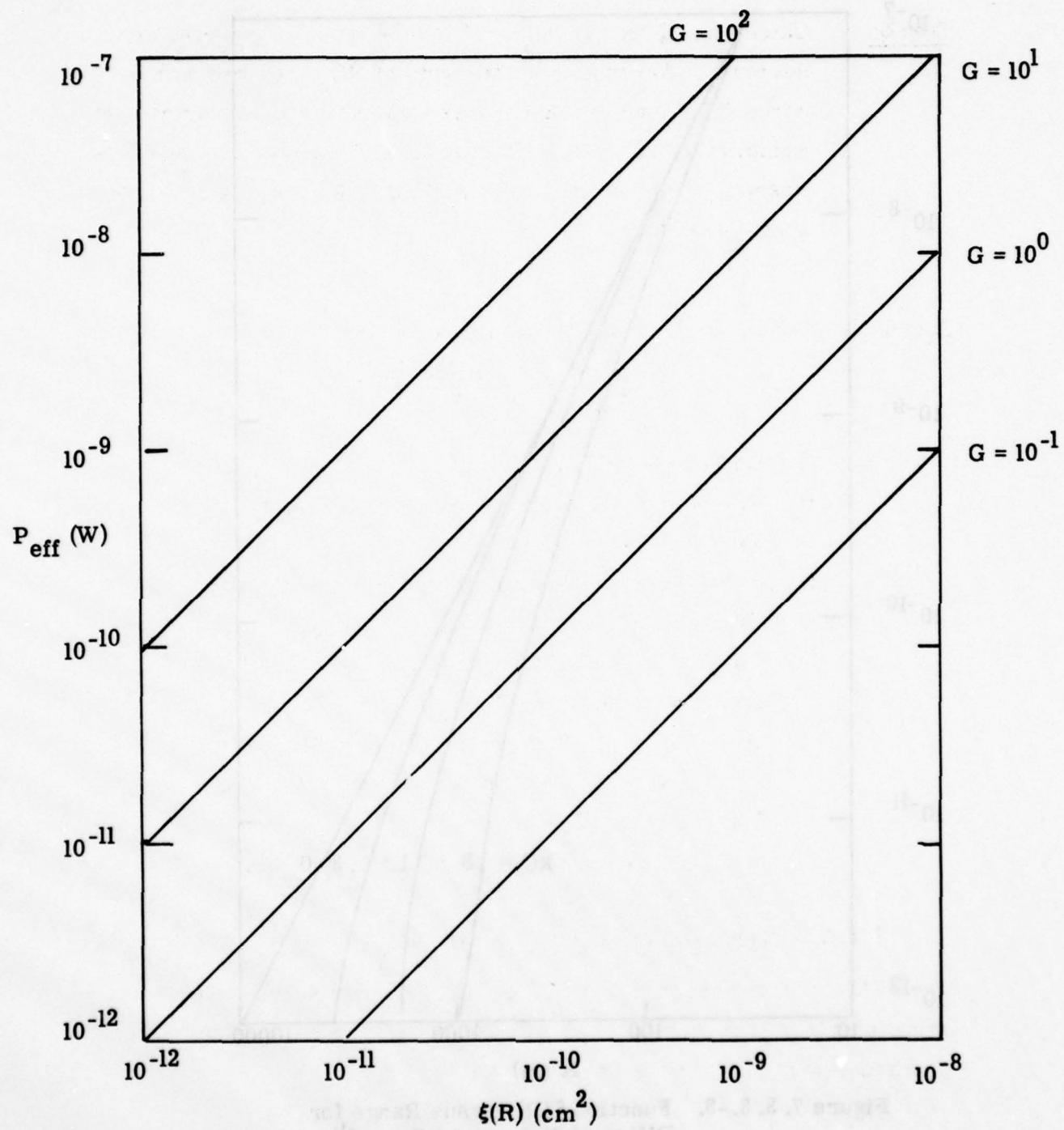


Figure 7. 3. 3-4.  $P_{\text{eff}}$  versus the Function  $\xi(R)$  for Different Values of  $G$

Step 5: Calculate: Q for (a)  $\text{NO}_x$ , and (b)  $\text{SO}_2$  and (c) hydrocarbons  
Assume: Absorption coefficients of  $\text{NO}_x$ ,  $\text{SO}_2$  and hydrocarbons for specific laser lines have not been determined yet.  
Actual calculation cannot be performed until data is available.  
Result: Q versus C to be plotted in Figure 7.3.3.-5 when data is available.

Step 6: Calculate: System Performance for SNR = 1, i.e.,

$$(P_{\text{eff}})_{\text{min}} = \frac{\sqrt{2} \text{NEP/F}}{Q}$$

- i) Determine NEP/F (Step 1)
- ii) Calculate Q for desired concentration (Step 5, Figure 7.3.3.-5)
- iii) Locate intersection between NEP/F and Q in Figure 7.3.3-6 and determine  $(P_{\text{eff}})_{\text{min}}$ .
- iv) For a given receiver optics area and overall efficiency, determine G from Figure 7.3.3-4.
- v) Determine  $\xi(R)$  from Figure 7.3.3-3 for given range and kC and establish  $P_{\text{eff}}$  for given G and  $\xi$  from Figure 7.3.3-4.
- vi) If  $(P_{\text{eff}}) > (P_{\text{eff}})_{\text{min}}$ , experiment is feasible.

#### 7.3.3.5 Special Performance Requirements

The general requirements applicable to all remote monitors were described in Section 7.1.1. For  $\text{SO}_2$ , THC and  $\text{NO}_x$  the special requirements were listed in Section 7.2.3.5.

7. 3. 3. 5b

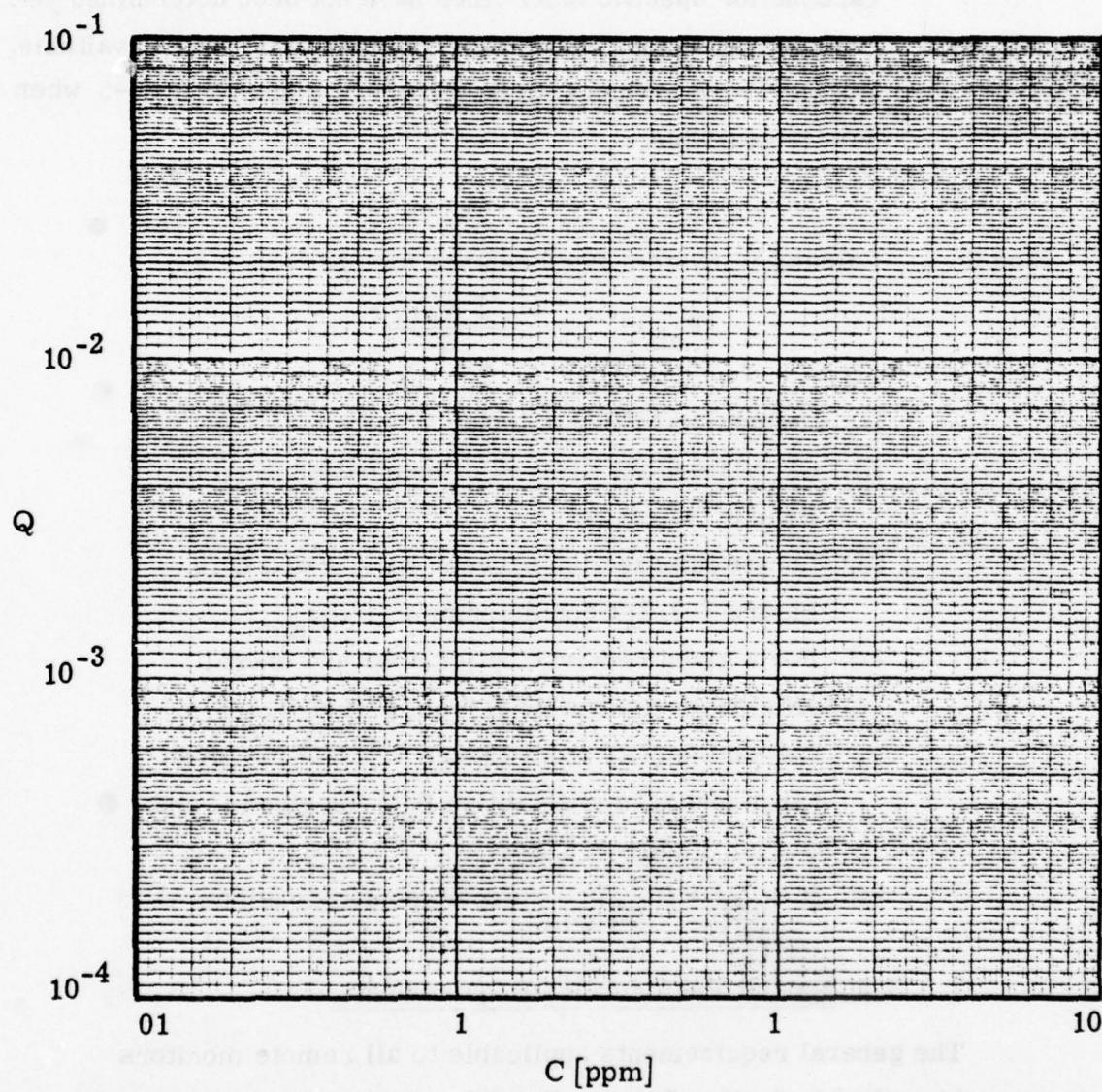


Figure 7. 3. 3-5.  $Q$  versus Concentration of  $\text{NO}_x$ ,  $\text{SO}_2$  and  $\langle \text{HC} \rangle$  for Different Ranges

See Step 5, Data required for this graph is not yet determined.

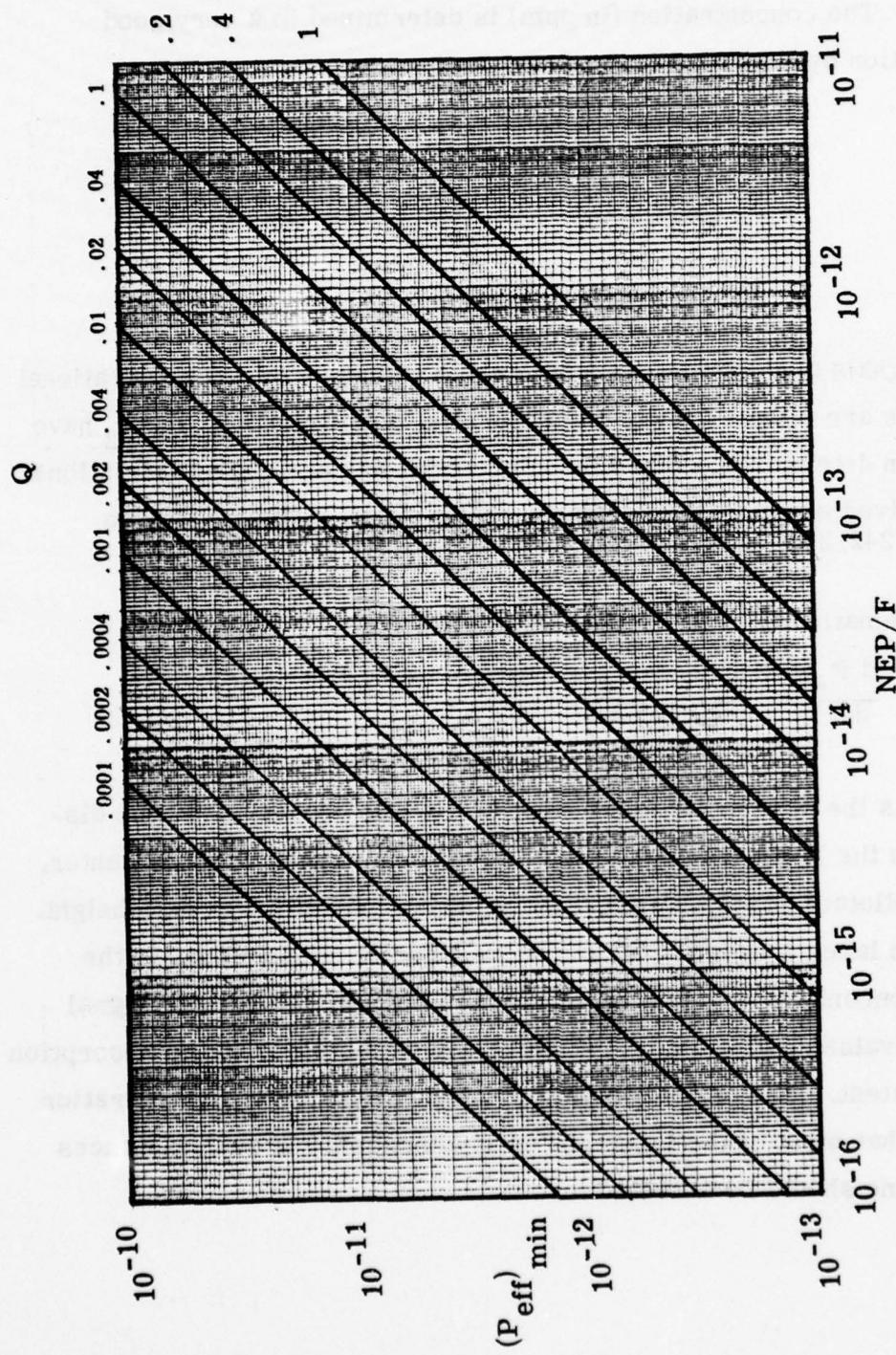


Figure 7. 3. 3--6.  $P_{\text{eff}}$  versus  $\text{NEP}/\text{F}$  for Different Values of  $Q$ .

### 7.3.3.6a

#### 7.3.3.6 Data Analysis Procedures

The concentration (in ppm) is determined in a very good approximation by:

$$C(\text{ppm}) = \frac{\ln Q}{2(k_1 - k_2) R}$$

where

$$Q = \frac{P(R)}{P'(R)}$$

The two signals are determined from analog signals. Because operational wavelengths are not yet known, the absorption coefficients  $k_1$  and  $k_2$  have not yet been determined. Since turbulence can introduce large variations in the received signals, the derivative/ratio signal method has been developed (242, 243).

Mathematically, this method is expressed as

$$\frac{1}{P_r} \frac{d P_r}{d\omega} = \frac{\delta P_r}{\delta k(\omega)} \frac{\delta k(\omega)}{\delta\omega} \frac{1}{P_r} = \frac{2 k_o l (\omega - \omega_o) c}{\gamma^2 [1 + (\omega - \omega_o)^2 / \gamma^2]^2}$$

where  $k_o$  is the absorption coefficient at the line center,  $l$  is the distance,  $\omega$  is the laser frequency,  $\omega_o$  is the frequency at the line center,  $c$  is the pollutant concentration, and  $\gamma$  is the half-width at half-height. For a given laser frequency the signal is directly proportional to the pollutant concentration. For maximum sensitivity, the ratioed signal should be evaluated at a laser frequency where the slope of the absorption line is greatest. The only exception is when the pollutant concentration is so high that most of the laser power is absorbed. In such instances a weaker line should be selected.

### 7. 3. 3. 6b

The signal [ $(dP_r/d\omega)/P_r$ ] as a function of pollutant concentration can be obtained from laboratory and/or field calibration. The calibration is made by using a gas cell with a known amount of pollutant gas. This can be done during the actual field test by observing the signal change after inserting the gas cell.

#### 7.3.4 UV/Visible Long-Path with Laser Source

##### 7.3.4.1 Principle of Operation

The measurement principle of ultraviolet/visible (UV/Visible) long-path transmission is used to obtain line-averaged concentrations of  $\text{SO}_2$  and  $\text{NO}_2$ . Laser beams at two different wavelengths in the 2000-5000 Å region are emitted and the transmitted signals are recorded. By differencing the wavelength-dependent signals, the average absorption of the pollutants can be determined. The concentration of the pollutant is proportional to the logarithm of the monochromatic transmission. The proportionality factor is the monochromatic absorption coefficient which must be known.

##### 7.3.4.2 System Description

The system consists of one or two lasers as transmitter, collecting optics which may be common to the transmitter and receiver, a detector, electronics and data display. A block diagram indicating the essential elements of a typical UV/visible long-path system is basically the same as was shown for the LWIR system in Figure 7.3.1-1, except that the IR detector is replaced by a photomultiplier or digicon tube. It should be noted that no prototype UV/visible long-path system using lasers has been tested as yet. The maximum permissible energy (MPE) for laser systems has been promulgated by DHEW in 21CFR1040.

##### 7.3.4.3 System Parameters

###### Commercially Available Lasers

$\text{N}_2$  Gas Laser

Xe Gas Laser

Neodymium Yag Solid State Laser

RDA Ruby

Dye Lasers

### 7. 3. 4. 3b

Other lasers that have transitions in the UV/visible region, but are not commercially available at present, include Ar, Cl, S, Kr, Ne, F, O<sub>2</sub>, P, B, Pb, Si, Se, In, and I. (Refs. 265 and 257). Both CW and pulsed lasers may be used.

#### Operational Wavelengths

Have not been determined yet.

#### Laser Energy

For  $2500 < \lambda < 4000 \text{ \AA}$ , the maximum permissible laser energy is  $10^{-3} \text{ W/cm}^2$  and for the visible spectrum,  $4000 < \lambda < 7000 \text{ \AA}$ , the laser energy is limited to  $10^{-6} \text{ W/cm}^2$ .

#### Detector

Commercially available detectors are photomultipliers or digicons having response curves S-13 or S-19. These tubes are very sensitive and have low noise figures. In general, the UV/visible receivers become shot and/or background noise limited.

#### Optics

Collecting Aperture	$A_o$
Solid Angle	$\Omega_o$
Optical Efficiency	$\eta_{opt}$
Detector Optics	$A_d \Omega_d (= A_o \Omega_o)$

These optical parameters are variables that must be chosen to fulfill the operational requirements (see below)

7. 3. 4. 4 Theoretical Performance Prediction

Based upon the selected system parameters, the performance can be predicted for a shot-noise-limited system. The signal-to-noise ratio for the determination of the pollutant concentration is given by

$$\text{SNR} = \frac{\ln Q^1}{dp \sqrt{(1/P)^2 + (1/P')^2}}$$

where

$$\begin{aligned}
 \ln Q^1 &= \ln \frac{P}{P'} \\
 P_1 &= (G/R^2)e^{-2k_1 C R} \\
 P' &= (G/R^2)e^{-2k_2 C R} \\
 G &= \eta P_t A_o \Gamma(R) \\
 \Gamma(R) &\approx 1/(\pi \Omega_L) \text{ for retroreflector} \\
 \Gamma(R) &= \rho'/\pi \text{ for topographical reflector} \\
 &\quad (\text{independent of } R \text{ if reflecting surface fills fov}) \\
 dp &= (P_{\text{eff}} h\nu/\eta t)^{1/2}
 \end{aligned}$$

The SNR may be simplified, i. e.,

$$\text{SNR} = \frac{Q}{2\pi} \left( \frac{\eta_Q t}{h\nu} P_{\text{eff}} \right)^{1/2}$$

### 7.3.4.4b

where

$$Q = 2 \sum (k_1 - k_2)_i C_i R$$

$$P_{\text{eff}} = G \xi(R)$$

$$\xi(R) = R^{-2} e^{-2kCR}$$

In the following a stepwise description for the calculation of SNR is given

Step 1: Calculate:  $G = \eta P_t A_o \Gamma(R)$

Assume:  $P_t = 10^{-2} \text{W}$  for  $3000-4000 \text{\AA}$  and  $10^{-5} \text{W}$  for  $4000-7000 \text{\AA}$ , using  $10 \text{ cm}^2$  laser beam area.

Result: Plot in Figure 7.3.4-1a and 1b shows  $G$  versus receiver aperture area  $A_o$  for five values of overall efficiency (optical and mechanical shutters) and  $\Gamma(R)$ .

Step 2: Calculate:  $\xi(R) = R^{-2} e^{-2kCR}$

Assume:  $kC = 0, .3, 1, 3 \text{ km}^{-1}$

Result: Plot in Figure 7.3.4-2 shows  $\xi(R)$  versus  $R$  for the above values of  $kC$ .

Step 3: Calculate:  $P_{\text{eff}} = G \xi(R)$

Assume: Useful range of  $R$  between 100 and 1000 m

$\xi(R)$  for different values of  $G$ .

Result: Plot in Figure 7.3.4-3 shows  $P_{\text{eff}}$  versus  $\xi(R)$  for various values of  $G$ .

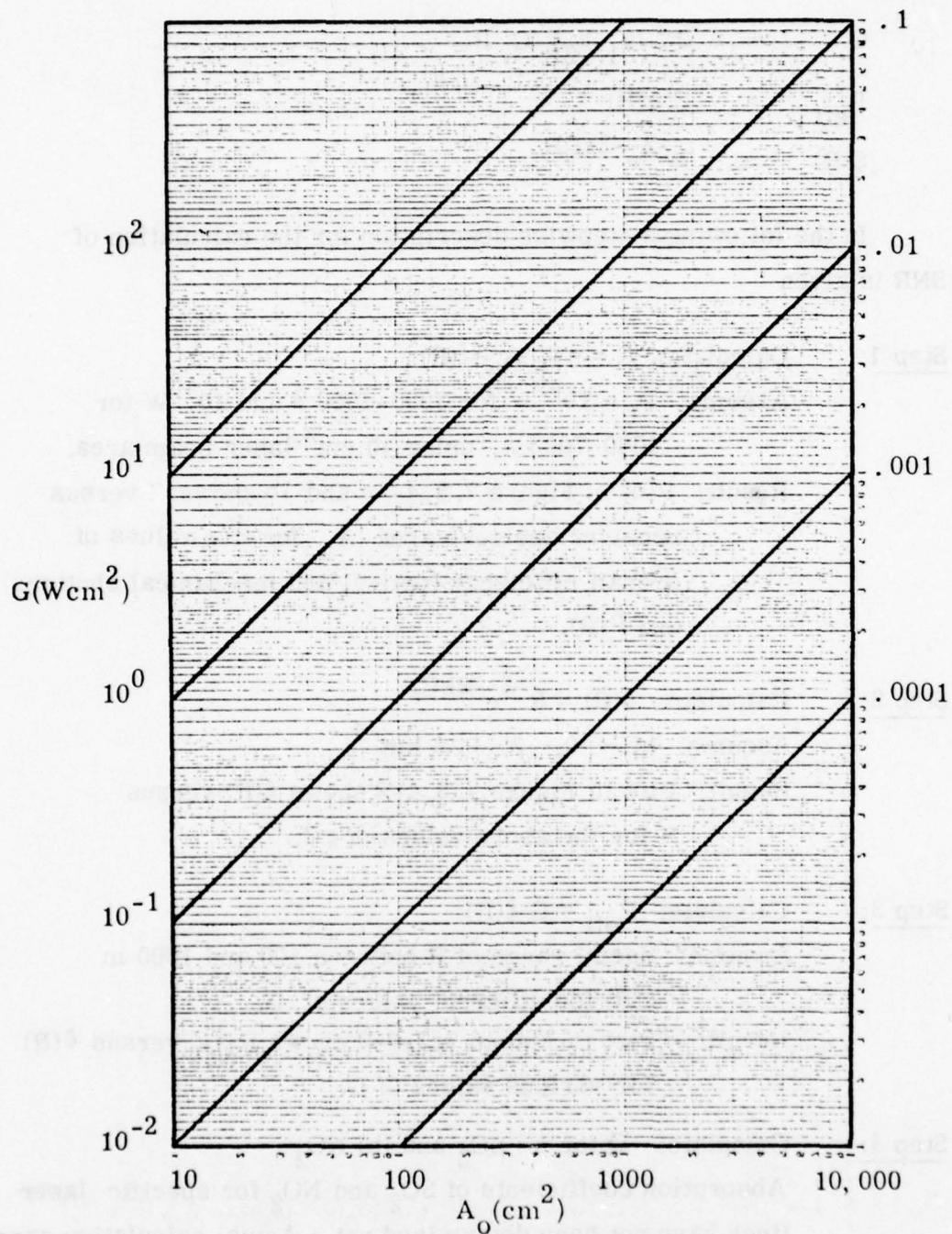
Step 4: Calculate:  $Q$  for (a)  $\text{SO}_2$  and (b)  $\text{NO}_2$

Absorption coefficients of  $\text{SO}_2$  and  $\text{NO}_2$  for specific laser lines have not been determined yet. Actual calculation cannot be performed until data is available.

Result:  $Q$  versus  $C$  to be plotted in Figure 7.3.4-4 when available.

7.3.4.4c

$$\eta \Gamma(R) = 1$$



**Figure 7.3.4-1a.** Function  $G$  versus  $A_0$  for Five Values of  $\eta\Gamma$ , using  $10^{-2}\text{W}$  for  $10\text{ cm}^2$  Laser Beam Area, Useful in Range  $3000-4000\text{ \AA}$ .

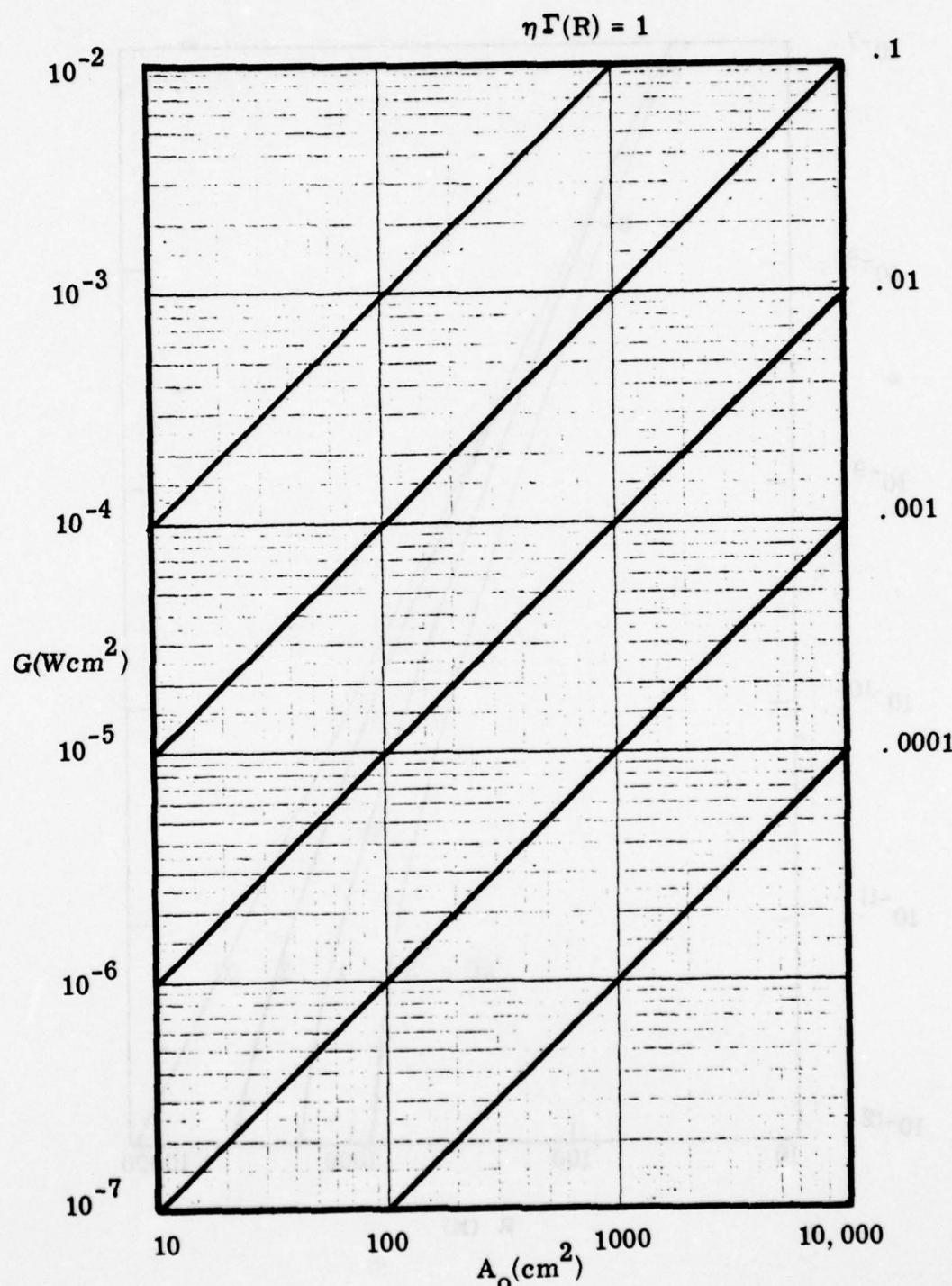


Figure 7. 3. 4-lb. Function  $G$  versus  $A_0$  for Five Values of  $\eta\Gamma$ , using  $P_t = 10^{-5}$  for  $10 \text{ cm}^2$  Laser Beam Area, Useful in the Visible Region from 4000 to 7000 Å.

7.3.4.4e

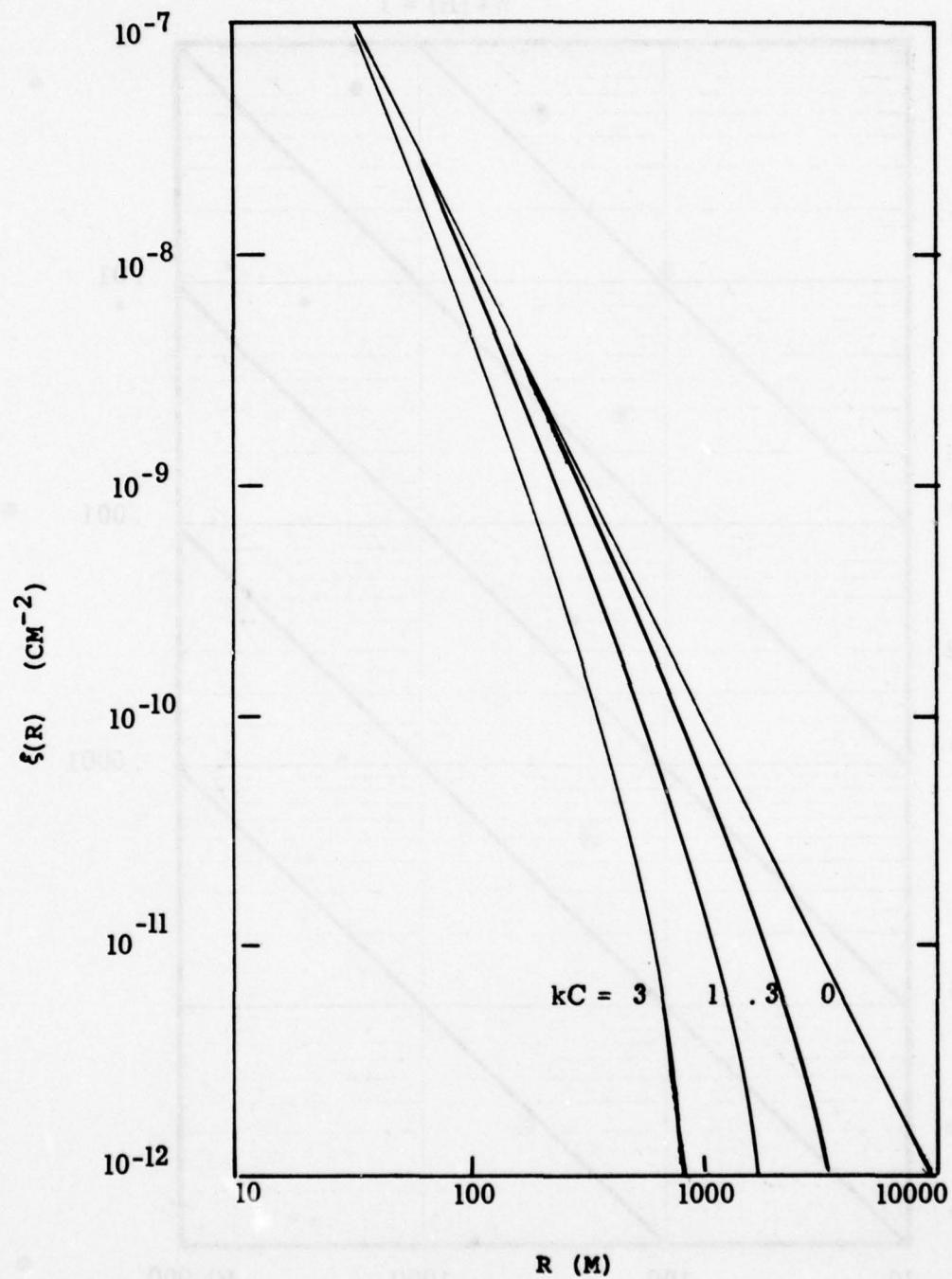


Figure 7.3.4.-2. Function  $\xi(R)$  vs. Range for Different Values of  $kC$  (km<sup>-1</sup>)

7. 3. 4. 4f

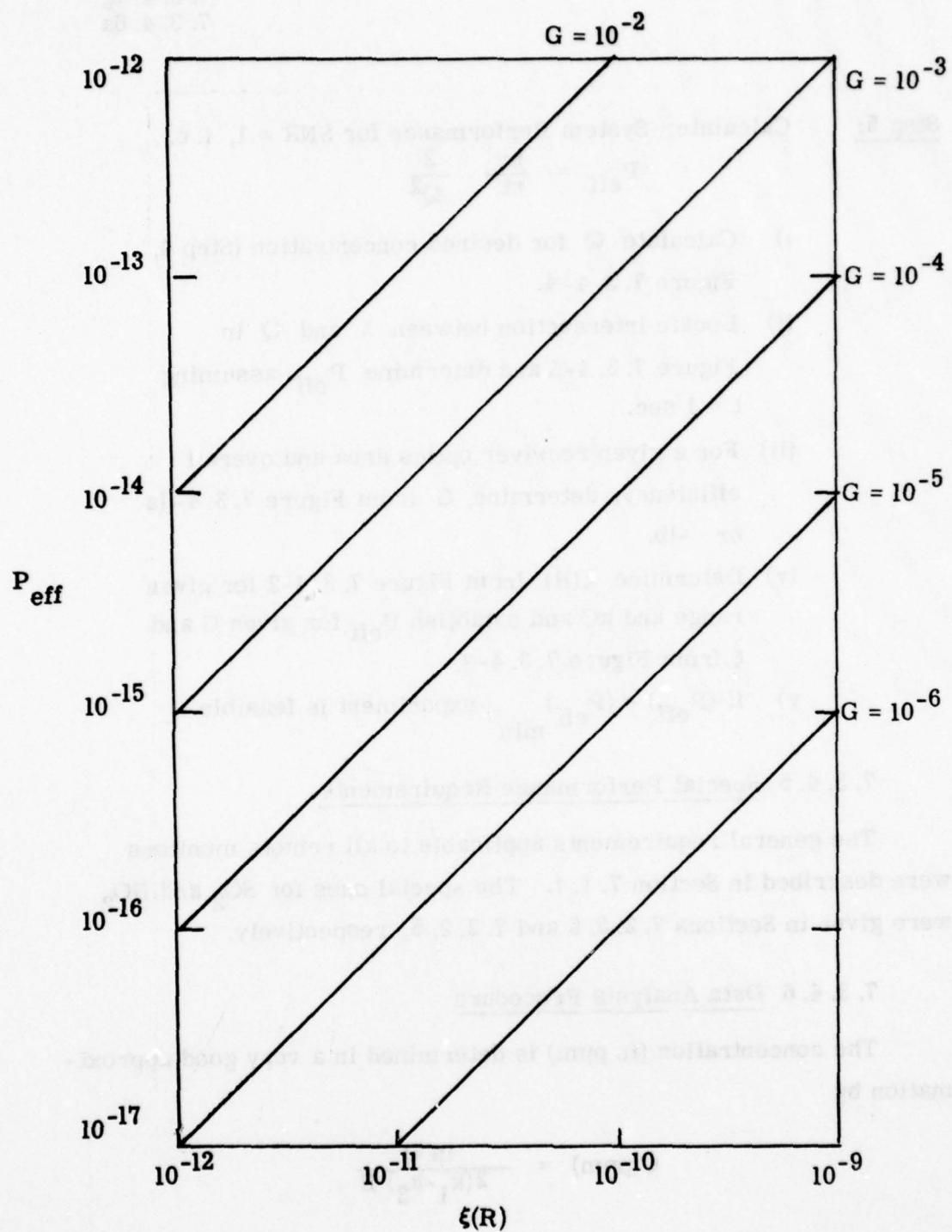


Figure 7. 3. 4-3.  $P_{\text{eff}}$  versus the Function  $\xi(R)$  for Different Values of  $G$ .

Step 5: Calculate: System Performance for SNR = 1, i. e.,

$$P_{\text{eff}} = \frac{h\nu}{\eta t} \frac{2}{Q^2}$$

- i) Calculate Q for desired concentration (Step 4, Figure 7. 3. 4-4).
- ii) Locate intersection between  $\lambda$  and Q in Figure 7. 3. 4-5 and determine  $P_{\text{eff}}$  assuming  $t = 1$  sec.
- iii) For a given receiver optics area and overall efficiency, determine G from Figure 7. 3. 4-1a or -lb.
- iv) Determine  $\xi(R)$  from Figure 7. 3. 4-2 for given range and kC and establish  $P_{\text{eff}}$  for given G and  $\xi$  from Figure 7. 3. 4-3.
- v) If  $(P_{\text{eff}}) > (P_{\text{eff}})_{\text{min}}$ , experiment is feasible.

#### 7. 3. 4. 5 Special Performance Requirements

The general requirements applicable to all remote monitors were described in Section 7. 1. 1. The special ones for  $\text{SO}_2$  and  $\text{NO}_2$  were given in Sections 7. 2. 3. 5 and 7. 2. 2. 5, respectively.

#### 7. 3. 4. 6 Data Analysis Procedure

The concentration (in ppm) is determined in a very good approximation by

$$C(\text{ppm}) = \frac{\ln Q}{2(k_1 - k_2) R}$$

7. 3. 4. 6b

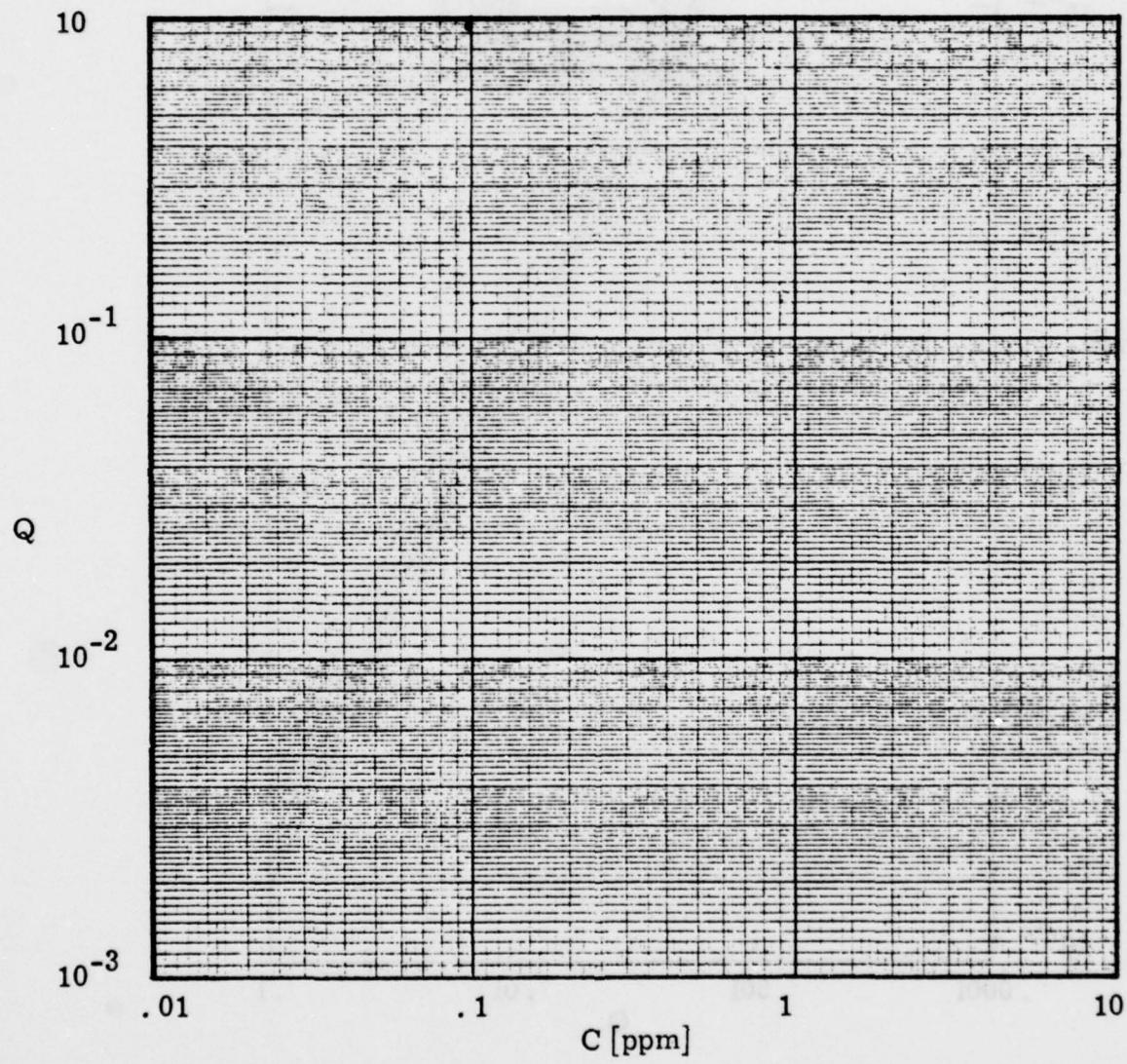


Figure 7.3.4-4. Q versus Concentration of  $\text{SO}_2$  and  $\text{NO}_2$  for a Resolution Element of 15 m.

See Step 4, Data required for this graph is not yet determined.

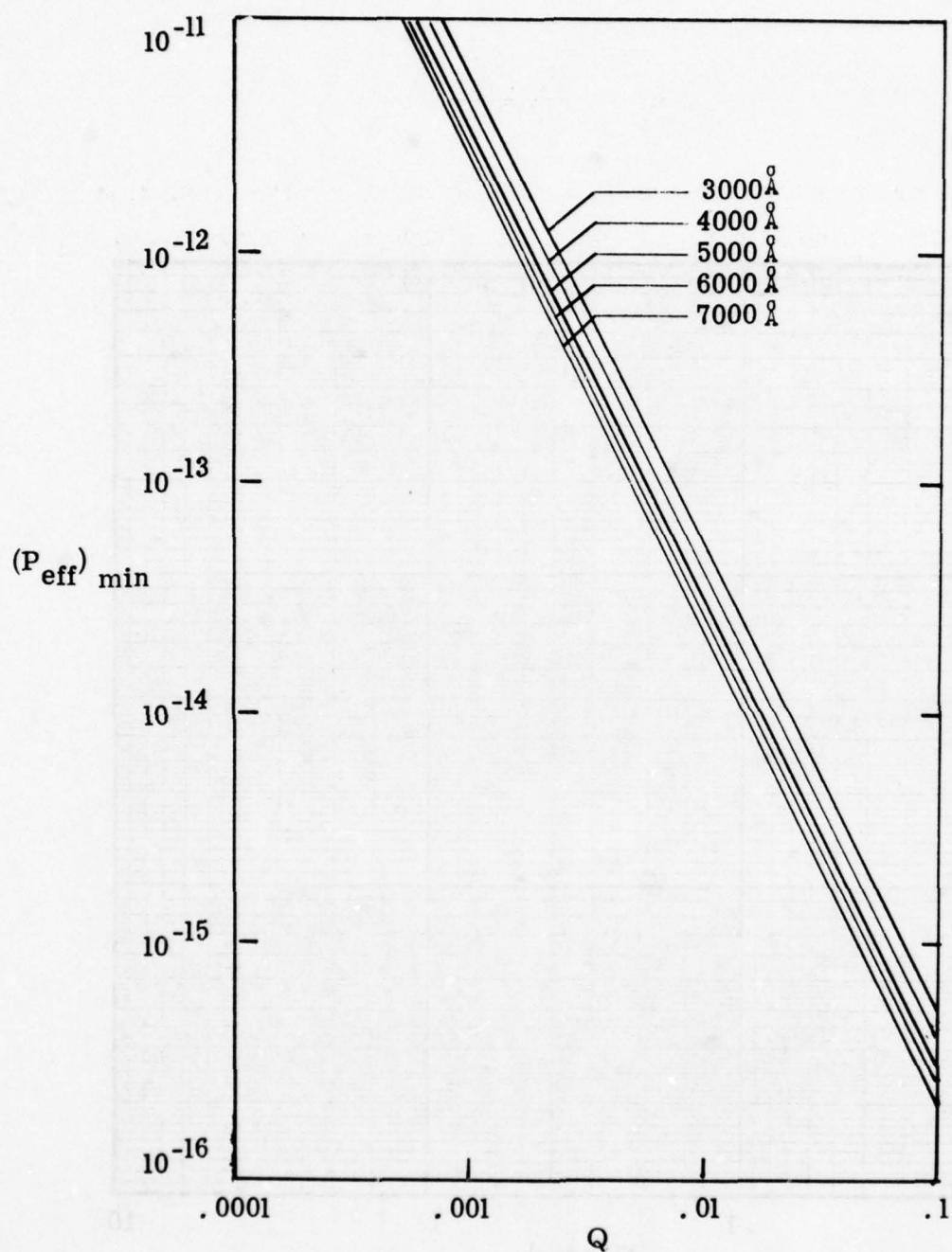


Figure 7.3.4-5.  $P_{\text{eff}}$  versus  $Q$  for  $3000 < \lambda < 7000 \text{ \AA}$ ,  
Assuming an Integration Time of .5  
sec and a Quantum Efficiency of 50%.

7. 3. 4. 6d

where

$$Q = \frac{P(R)}{P(R)}$$

The two signals are determined from analog signals. The absorption coefficients  $k_1$  and  $k_2$  have not been determined yet, because the exact operational wavelengths are not yet established.

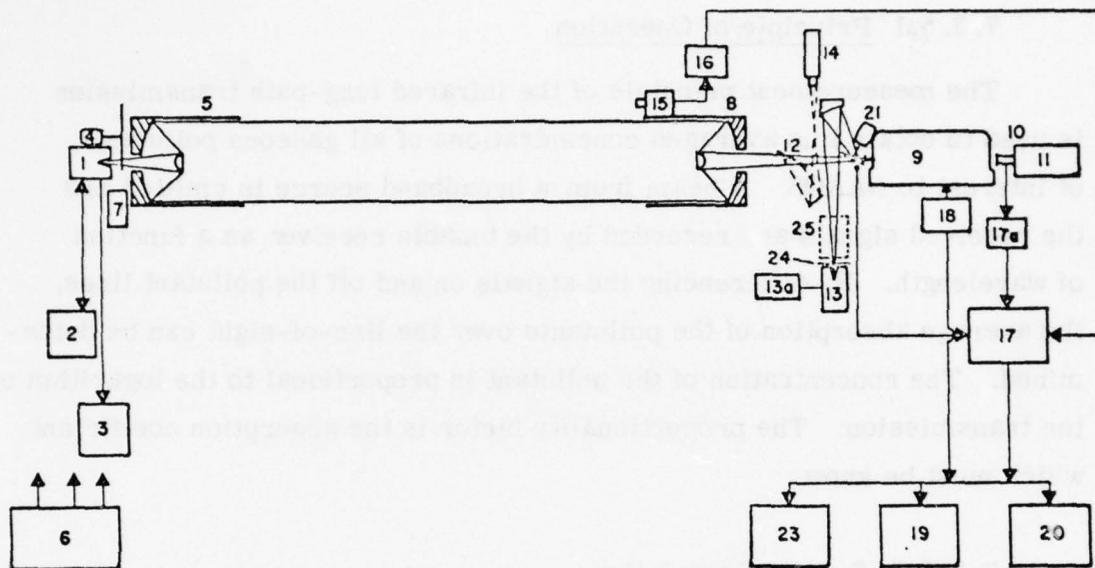
### 7.3.5 IR Long-Path with Broadband Source and Dispersive Receiver

#### 7.3.5.1 Principle of Operation

The measurement principle of the infrared long-path transmission is used to obtain line averaged concentrations of all gaseous pollutants of interest to NAAQS. A beam from a broadband source is emitted and the received signals are recorded by the tunable receiver as a function of wavelength. By differencing the signals on and off the pollutant lines, the average absorption of the pollutants over the line-of-sight can be determined. The concentration of the pollutant is proportional to the logarithm of the transmission. The proportionality factor is the absorption coefficient which must be known.

#### 7.3.5.2 System Description

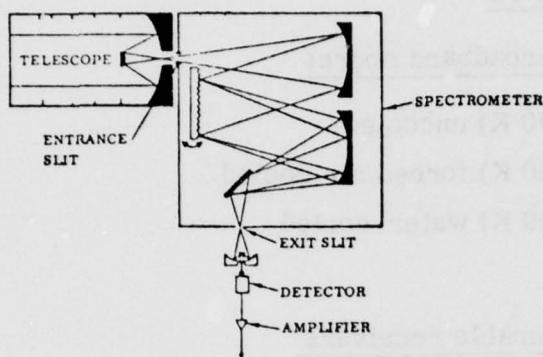
The system consists of a broadband source, such as a blackbody, collecting optics and receiver consisting of a tunable spectrometer, electronics and data display. A block diagram indicating the essential elements of a typical system is shown in Figure 7.3.5-1. Two different kinds of spectrophotometers are shown in Figure 7.3.5-2.



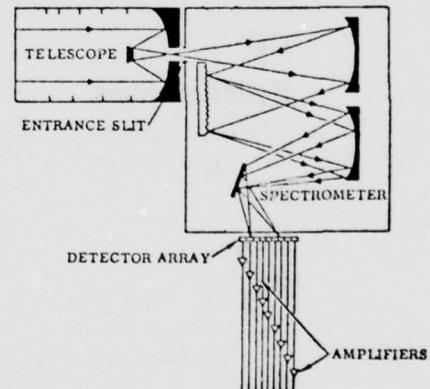
**Figure 7.3.5-1.** Schematic of a Long-Path Monitor, Using a Blackbody as Illuminator Adopted from Ref. 165. The Components are:

- |                                   |                              |
|-----------------------------------|------------------------------|
| 1. Blackbody                      | 13a. Temperature Controller  |
| 2. Temperature Controller         | 14. Telescope                |
| 3. Continuous Temperature Readout | 15. InAs Detector            |
| 4. Chopper                        | 16. Preamplifier             |
| 5. Source Optics                  | 17. Amplifying System        |
| 6. Power Generator                | 17a. Preamplifier            |
| 7. Boresight Microscope           | 18. Wavelength Drive         |
| 8. Receiver Optics                | 19. DVM-Digital Readout      |
| 9. Spectrometer                   | 20. Strip Chart Recorder     |
| 10. Ge:Hg Detector                | 21. Chopper                  |
| 11. Mechanical Cooler             | 22. Power Supply (not shown) |
| 12. 2 Position Mirror             | 23. Magnetic Tape            |
| 13. Calibration Blackbody         | 24. Precision Aperture       |
|                                   | 25. Gas Cell                 |

7. 3. 5. 2c



Monochromator



Polychromator

Figure 7. 3. 5-2. Two Different Kinds of Tunable Receivers Using a Dispersive Element (Grating).

7. 3. 5. 3 System ParametersCommercially available broadband source

Blackbody (~ 1200 K) uncooled  
 (~ 1500 K) forced air cooled  
 (~ 1800 K) water-cooled

Nernst glower

Commercially available tunable receivers

Monochromator (single and double pass)  
 Polychromator

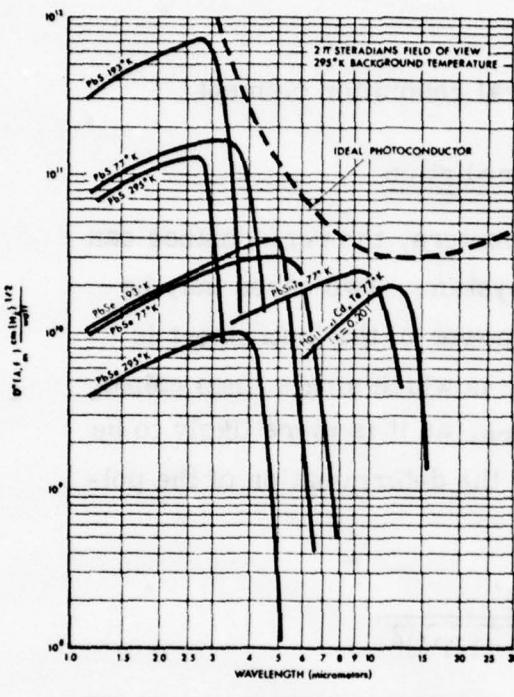
Operational wavelength regions

CO	4. 5 - 4. 8 $\mu\text{m}$
Hydrocarbons	3. 0 - 4. 0 $\mu\text{m}$
	9. 5 - 12. 0 $\mu\text{m}$
NO	5. 1 - 5. 5 $\mu\text{m}$
NO <sub>2</sub>	3. 3 - 3. 6 $\mu\text{m}$
SO <sub>2</sub>	3. 95 - 4. 05 $\mu\text{m}$
	8. 4 - 9. 0 $\mu\text{m}$
O <sub>3</sub>	9. 4 - 9. 8 $\mu\text{m}$

Detector

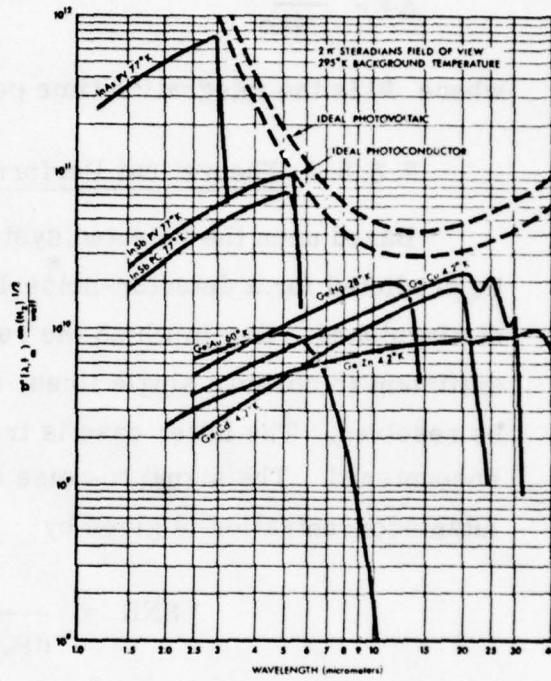
Commercially available detectors in the infrared are shown in the following graphs (Figures 7. 3. 5-3a and -3b):

### 7.3.5.3b



SPECTRAL DETECTIVITIES FOR ABOVE-AVERAGE DETECTORS FABRICATED BY SBRC.  
A REDUCTION IN BACKGROUND PHOTON FLUX PRODUCES HIGHER DETECTIVITIES

Figure 7.3.5-3a



SPECTRAL DETECTIVITIES FOR ABOVE-AVERAGE DETECTORS FABRICATED BY SBRC.  
A REDUCTION IN BACKGROUND PHOTON FLUX PRODUCES HIGHER DETECTIVITIES

Figure 7.3.5-3b

### Optics

Collecting Aperture

$$A_o$$

Solid Angle

$$\Omega_o$$

Optical Efficiency

$$\eta_{opt}$$

Detector Optics

$$A_d \Omega_d (= A_o \Omega_o)$$

These optical parameters are variables that must be chosen to fulfill the operational requirements (shown in the following).

Electronic Bandpass

$$\Delta f = \frac{1}{4t_c}$$

where  $t_c$  is the integration time per spectral resolution element.

7. 3. 5. 4 Theoretical Performance Prediction

Based upon the selected system parameters, the performance can be predicted for a detector -noise-limited system. Two cases may be distinguished. One in which the resolving power of the instrument is sufficient to observe single lines, the other in which single lines cannot be resolved. The latter case is treated here, as it is more likely to be encountered. The signal-to-noise ratio for the determination of the pollutant concentration is given by

$$SNR = \frac{\ln Q'}{dP\sqrt{(1/P)^2 + (1/P')^2}}$$

where

$$\ln Q' = \ln P/P'$$

$$P = G/R e^{-(w/d)}_1 \Delta \lambda$$

$$P' = G/R e^{-(w/d)}_2 \Delta \lambda$$

$$G = \eta A^2 N^0 (\zeta, T)$$

$$w/d = kCR(1+kCR/4a)^{-1/2}$$

$$dP = (A_d/4t_c)^{1/2} / D^*$$

For these expressions,  $w/d$  is the line width to line spacing ratio.

### 7.3.5.4b

The SNR may be simplified, i.e.,

$$\text{SNR} = \frac{Q P_{\text{eff}}}{\sqrt{2 \text{ NEP}}}$$

where

$$Q = (w/d)_2 - (w/d)_1$$

$$P_{\text{eff}} = G \xi(R) \Delta \lambda$$

$$\xi(R) = R^{-2} e^{-(w/d)}$$

In the following a stepwise description for the calculation of SNR is given

Step 1: Calculate: NEP

Assume:  $D^* = 3 \times 10^{10} \text{ cm Hz}^{1/2} \text{W}^{-1}$  (representative for MWIR to LWIR)

$D^* = 3 \times 10^{11} \text{ cm Hz}^{1/2} \text{W}^{-1}$  (representative for SWIR)

Result: Plot in Figure 7.3.5-4 shows NEP versus  $A_d$  for different integration times.

Step 2: Calculate: G

Assume:  $T = 1600 \text{ K}$

$$\eta = .1$$

Result: Plot in Figure 7.3.5-5 shows G versus  $\lambda$  for different values of  $A_o$ .

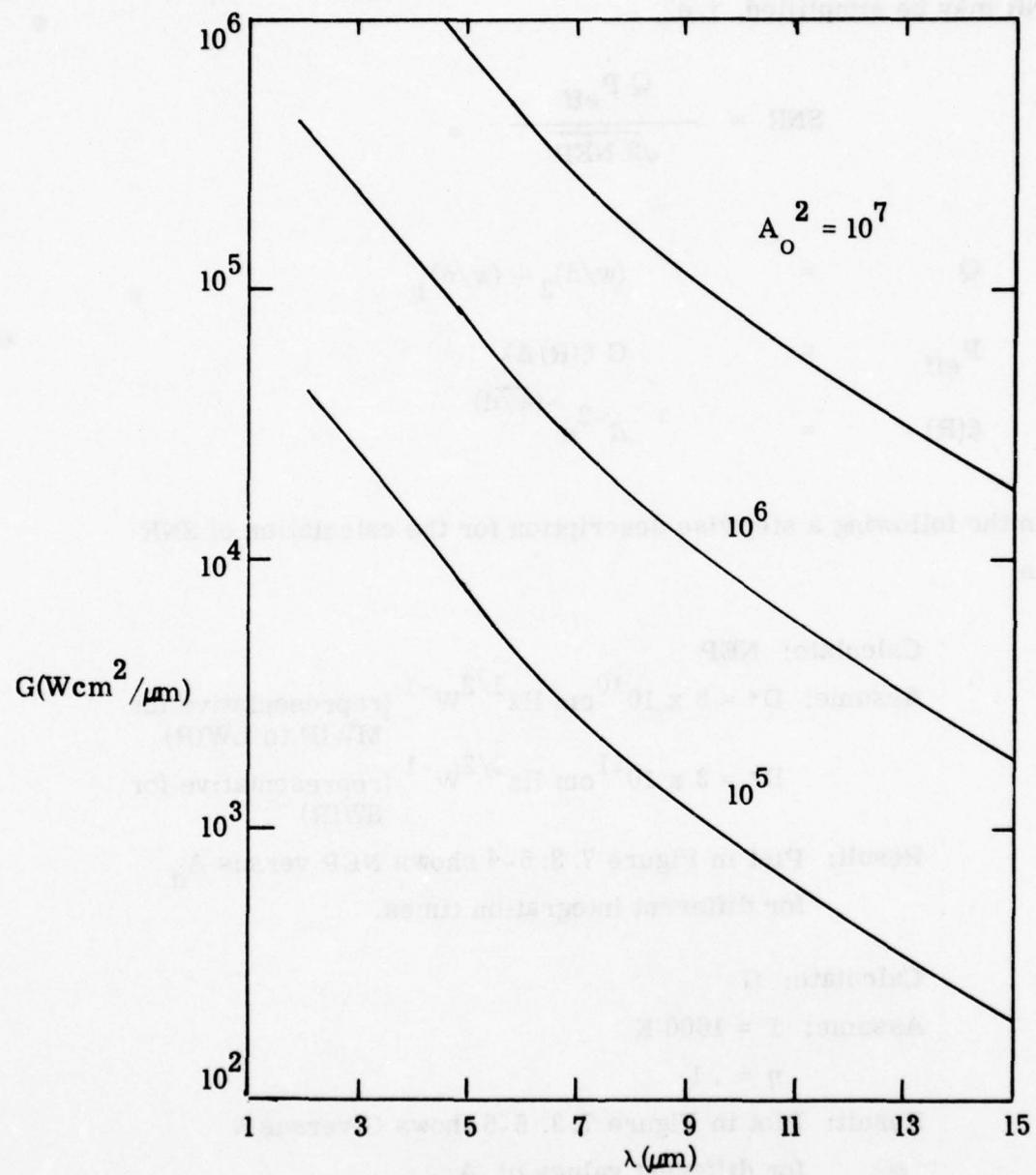
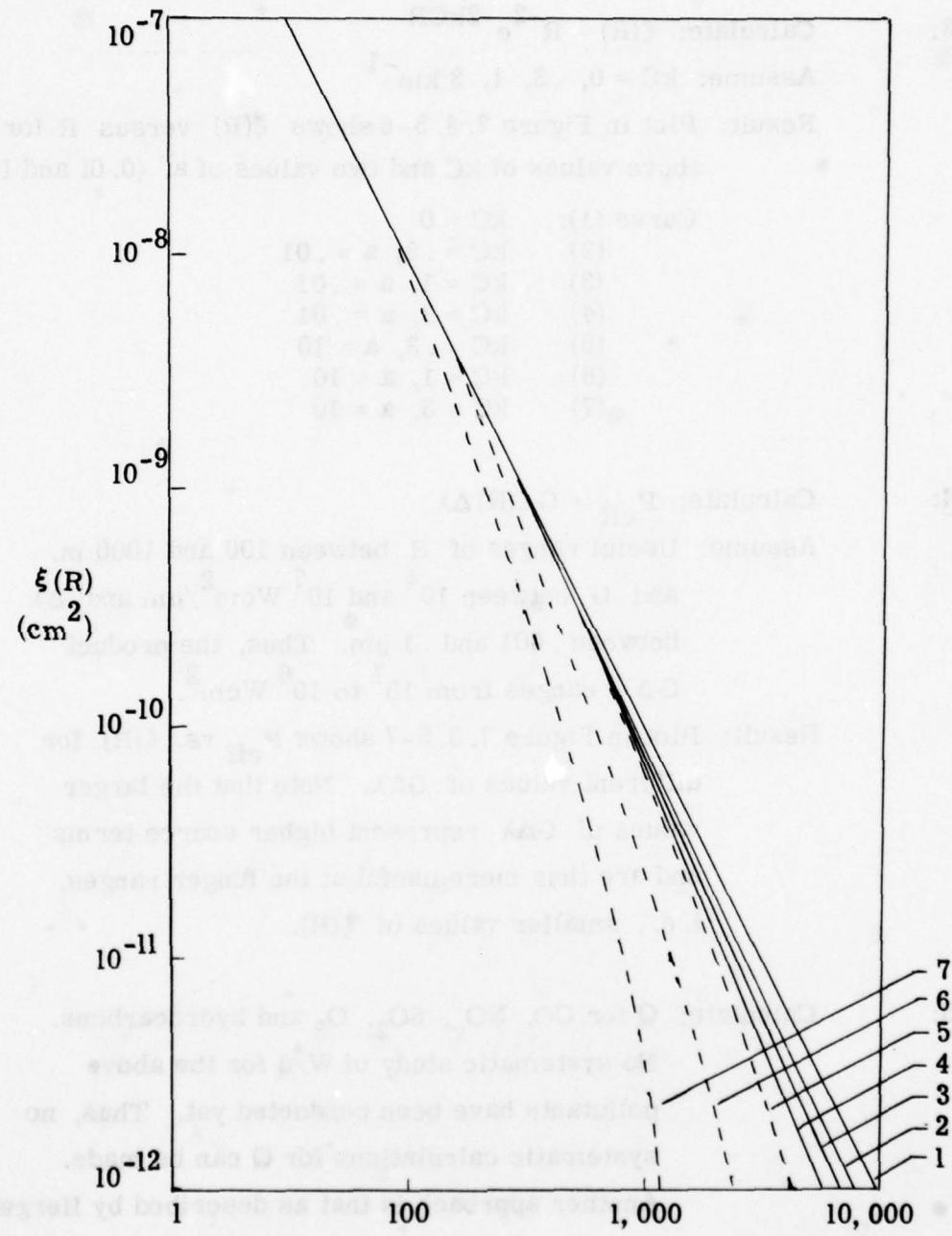


Figure 7.3.5-5.  $G$  versus  $\lambda$  for Three Different Values of  $A_0^2$



**Figure 7.3.5-6.**  $\xi(R)$  versus  $R$  for Different Values of  $kC$  and  $a$ : Curve (1)  $kC = 0$ ; Curve (2)  $kC = .3$ ,  $a = .01$ ; (3)  $kC = 1$ ,  $a = .01$ ; (4)  $kC = 3$ ,  $a = .01$ ; (5)  $kC = .3$ ,  $a = 10$ ; (6)  $kC = 1$ ,  $a = 10$ ; (7)  $kC = 3$ ,  $a = 10$

7. 3. 5. 4e

Step 3:

Calculate:  $\xi(R) = R^{-2} e^{-2kCR}$

Assume:  $kC = 0, .3, 1, 3 \text{ km}^{-1}$

Result: Plot in Figure 7. 3. 5-6 shows  $\xi(R)$  versus  $R$  for the above values of  $kC$  and two values of  $a$ . (0.01 and 10).

- Curve (1):  $kC = 0$   
(2)  $kC = .3, a = .01$   
(3)  $kC = 1, a = .01$   
(4)  $kC = 3, a = .01$   
(5)  $kC = .3, a = 10$   
(6)  $kC = 1, a = 10$   
(7)  $kC = 3, a = 10$

Step 4:

Calculate:  $P_{\text{eff}} = G \xi(R) \Delta\lambda$

Assume: Useful ranges of  $R$  between 100 and 1000 m, and  $G$  between  $10^4$  and  $10^7 \text{ Wcm}^2/\mu\text{m}$  and  $\Delta\lambda$  between .001 and .1  $\mu\text{m}$ . Thus, the product  $G\Delta\lambda$  ranges from  $10^1$  to  $10^6 \text{ Wcm}^2$ .

Result: Plot in Figure 7. 3. 5-7 shows  $P_{\text{eff}}$  vs.  $\xi(R)$  for different values of  $G\Delta\lambda$ . Note that the larger values of  $G\Delta\lambda$  represent higher source terms and are thus more useful at the longer ranges, i. e., smaller values of  $\xi(R)$ .

Step 5:

Calculate:  $Q$  for CO,  $\text{NO}_x$ ,  $\text{SO}_2$ ,  $\text{O}_3$  and hydrocarbons.

No systematic study of  $W/d$  for the above pollutants have been conducted yet. Thus, no systematic calculations for  $Q$  can be made.

Another approach is that as described by Herget<sup>(246)</sup>, whereby the signals obtained from the absorption of the pollutant in an absorption cell is related to the signal obtained in the field (see Section 5. 3. 2. 2).

7.3.5.4g

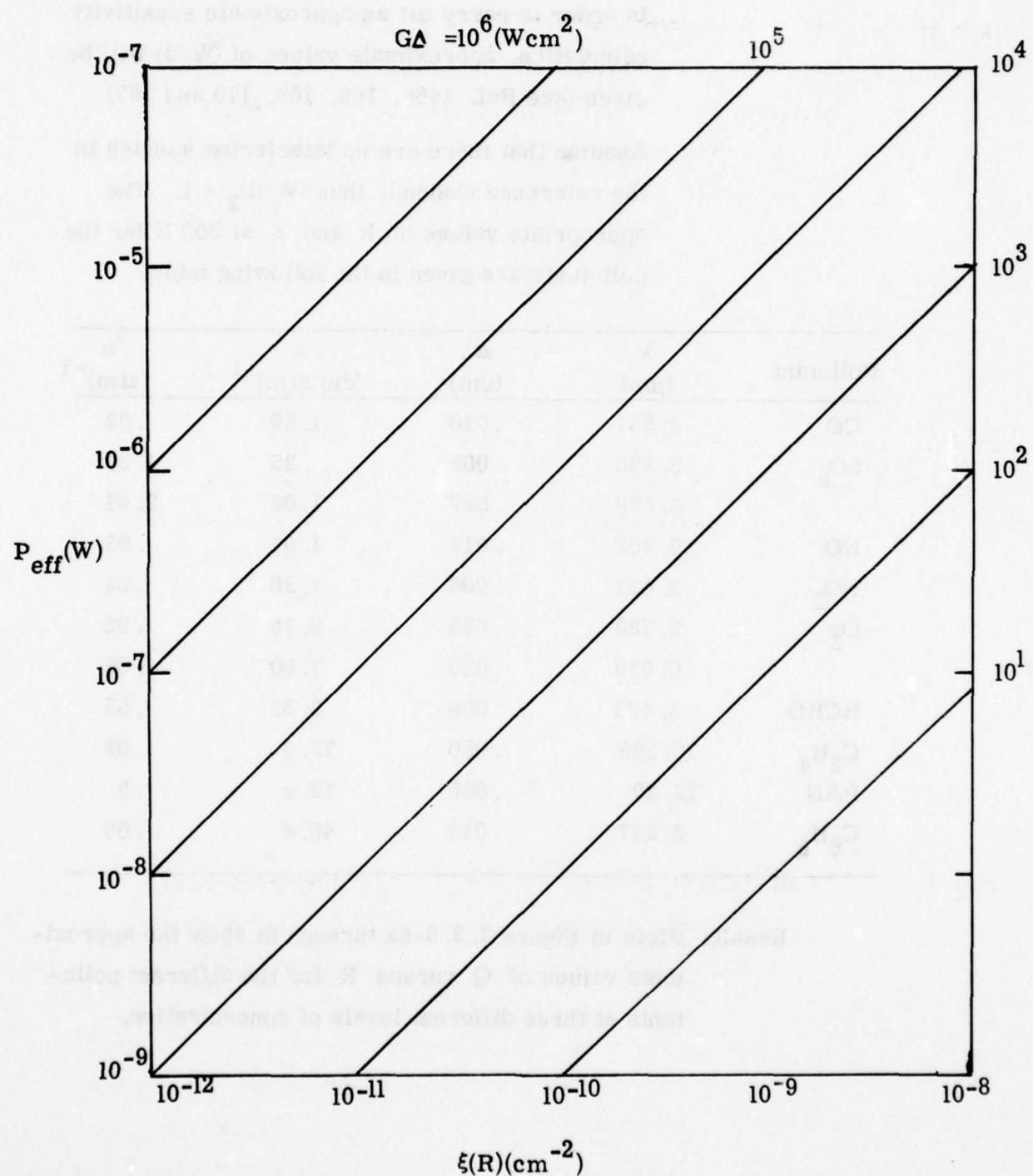


Figure 7.3.5-7.  $P_{\text{eff}}$  versus  $\xi(\text{R})$  for Different Values of  $G\Delta\lambda$ .

## 7.3.5.4h

In order to carry out an approximate sensitivity calculation, approximate values of (W/d) will be given (see Ref. 146a, 166, 169, 176 and 267).

Assume that there are no interfering species in the reference channel, thus  $(W/d)_2 = 1$ . The appropriate values of k and a at 300 K for the pollutants are given in the following table.

Pollutant	$\lambda$ ( $\mu\text{m}$ )	$\Delta\lambda$ ( $\mu\text{m}$ )	$k$ $(\text{cm atm})^{-1}$	$a_0$ $(\text{atm})^{-1}$
CO	4.551	.010	1.59	.02
$\text{SO}_2$	3.996	.008	.25	1.39
	8.639	.037	1.08	2.44
NO	5.202	.014	1.01	.08
$\text{NO}_2$	3.422	.006	1.20	.93
$\text{O}_3$	9.722	.060	9.15	.05
	0.530	.050	7.90	.05
HCHO	3.433	.006	3.52	.55
$\text{C}_2\text{H}_4$	10.563	.050	73.0	.03
PAN	12.20	.065	12.4	.5
$\text{C}_6\text{H}_6$	3.287	.011	46.4	.08

Result: Plots in Figure 7.3.5-8a through 8i show the approximate values of Q versus R for the different pollutants at three different levels of concentration.

7. 3. 5. 4i

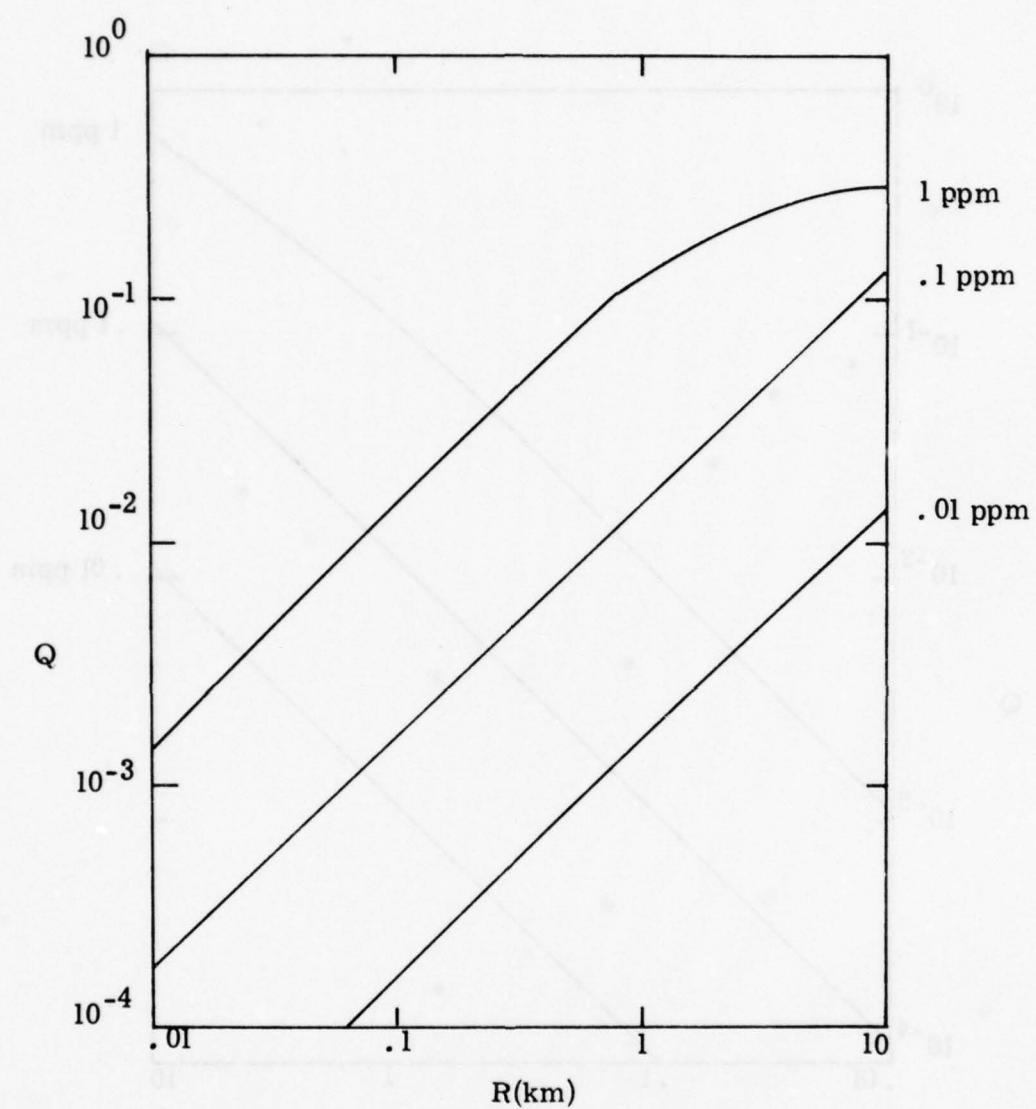


Figure 7. 3. 5-8a.  $Q$  for CO versus range for three levels of concentration.

7. 3. 5. 4j

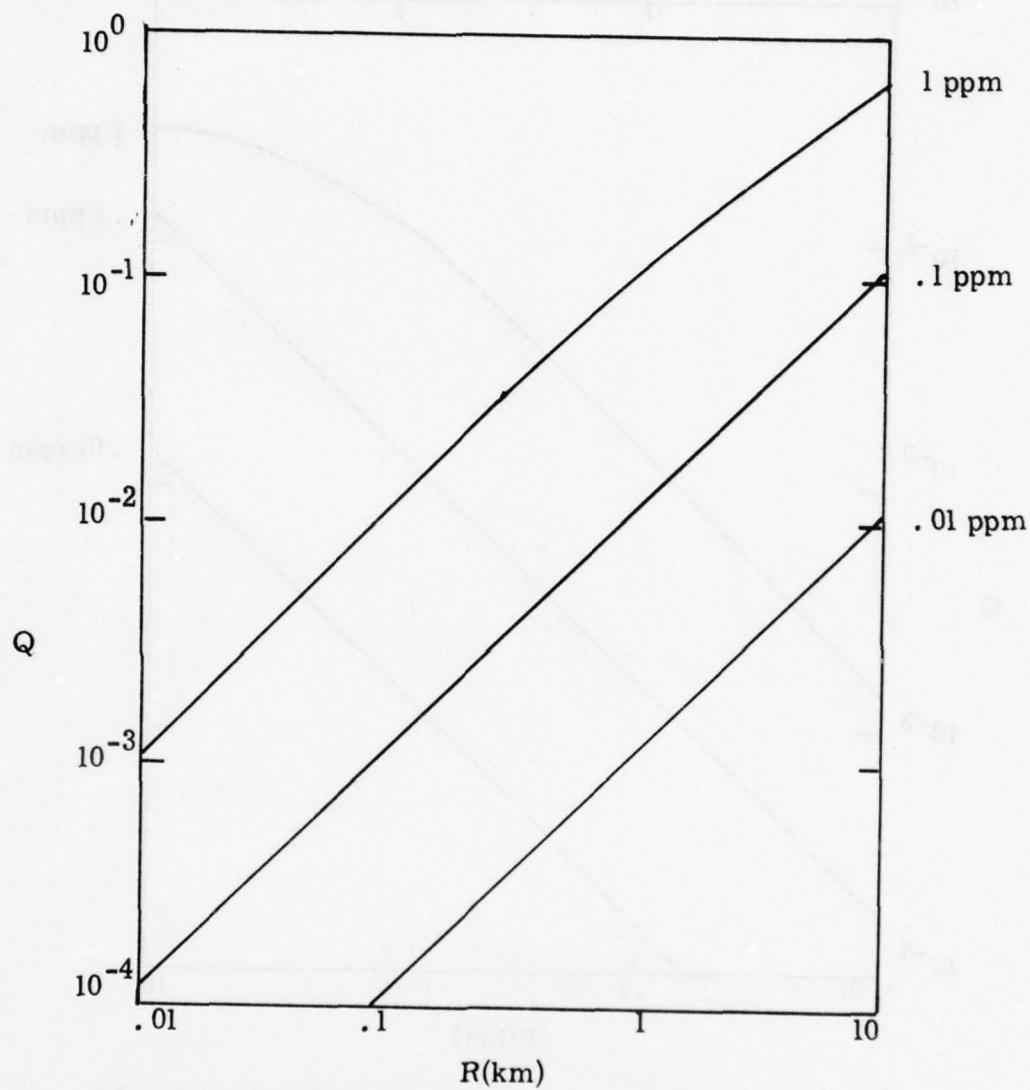


Figure 7. 3. 5-8b  $Q$  for  $\text{SO}_2$  versus range for three levels of concentration .

7.3.5.4k

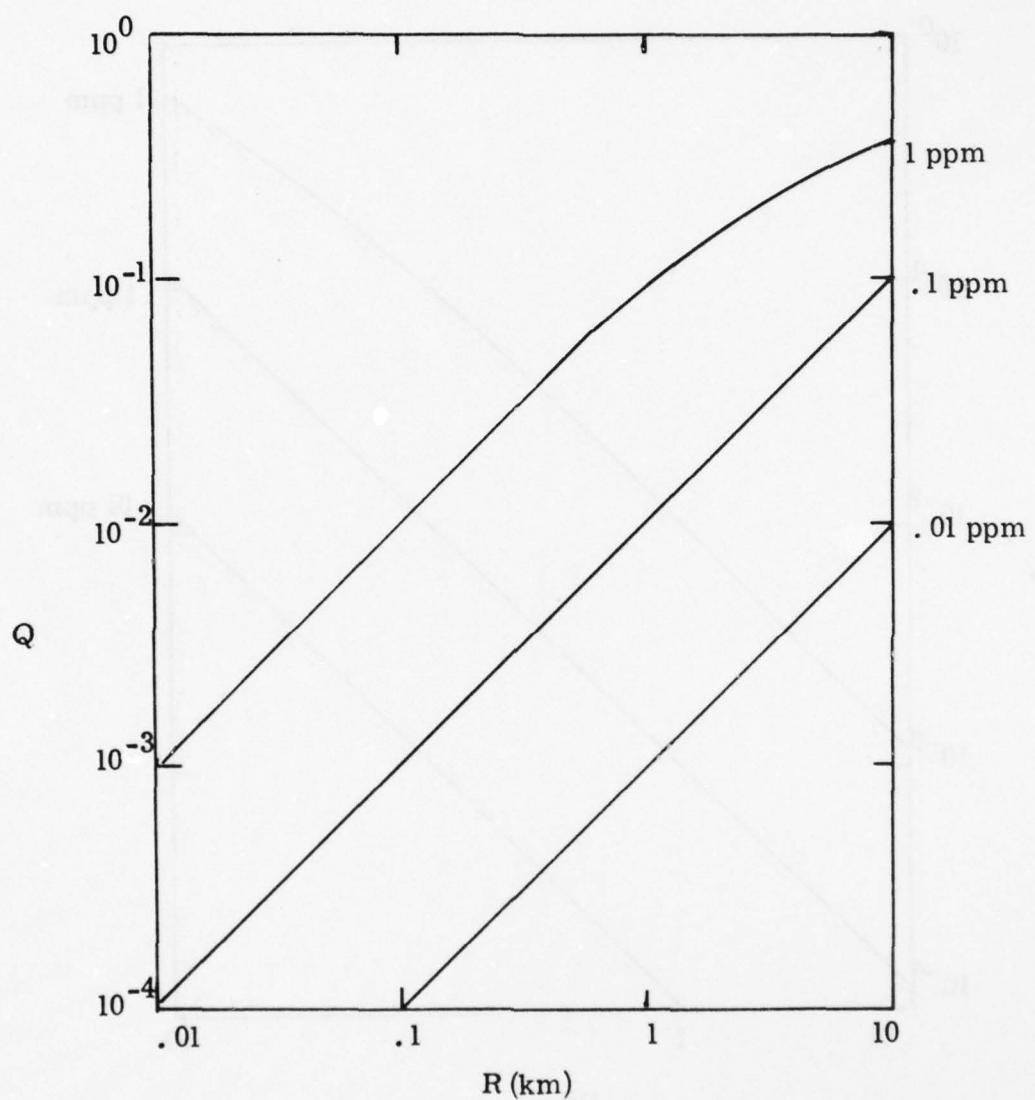


Figure 7.3.5-8c.  $Q$  for NO versus range for three levels of concentration.

7.3.5.41

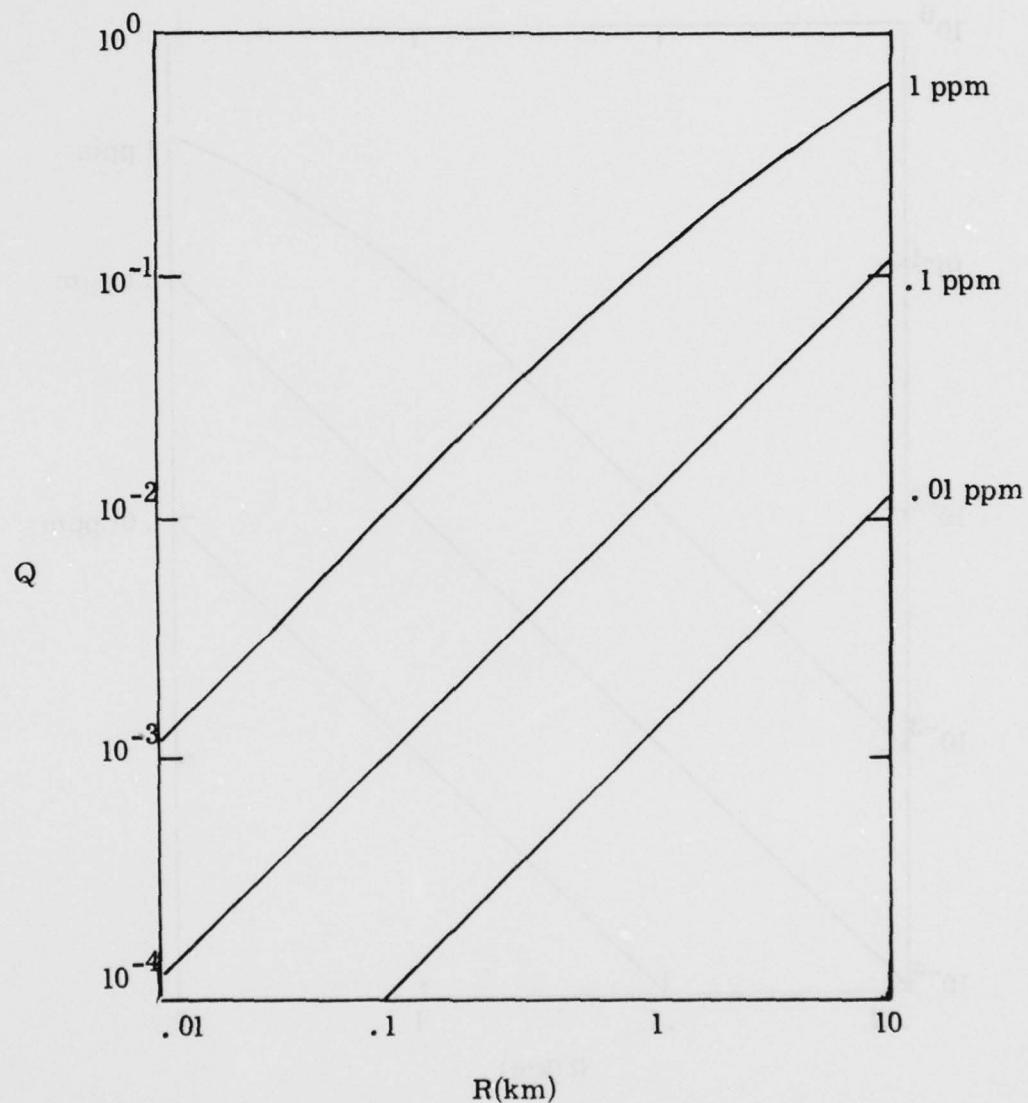


Figure 7.3.5-8d.  $Q$  for  $\text{NO}_2$  versus range for three levels of concentration.

7. 3. 5. 4m

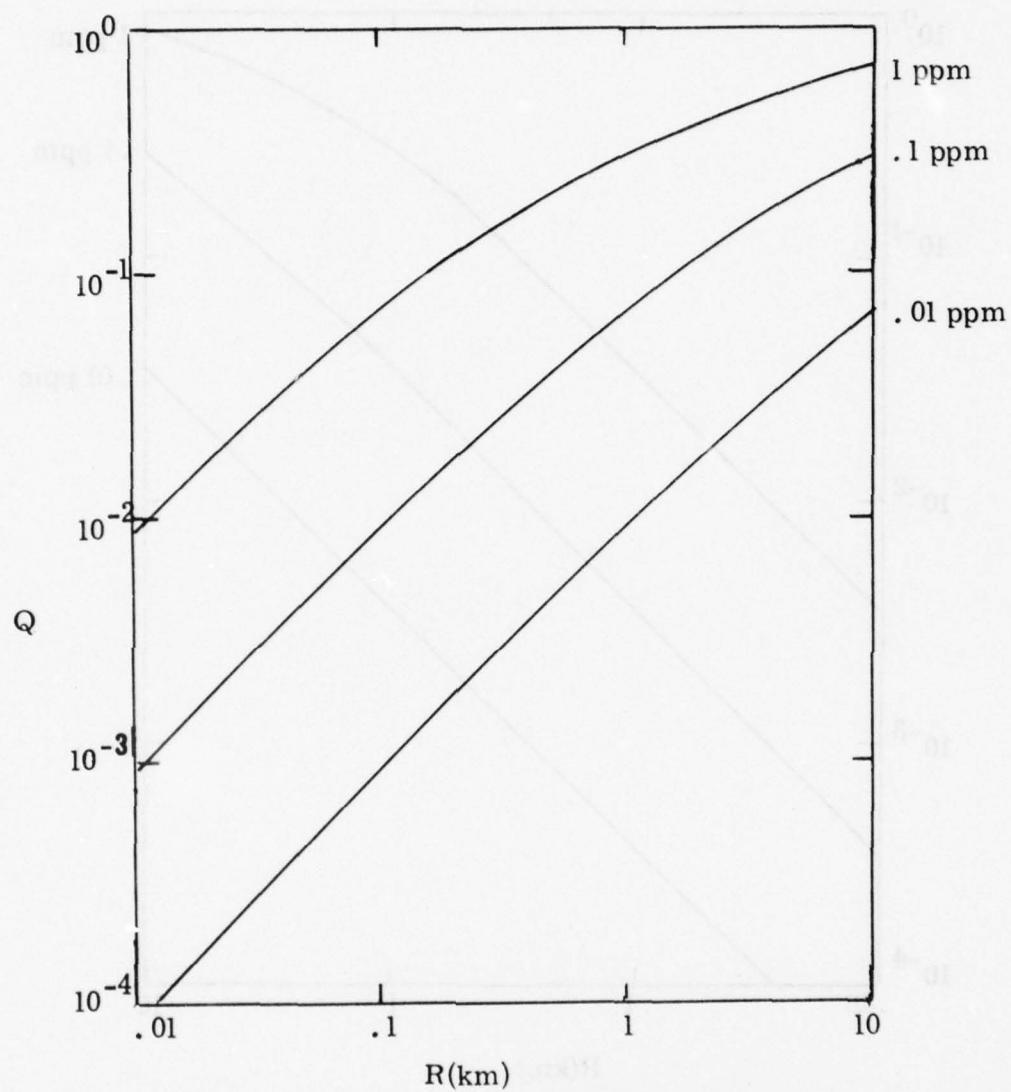


Figure 7. 3. 5-8e.  $Q$  for  $\text{O}_3$  versus range for three levels of concentration.

7.3.5.4n

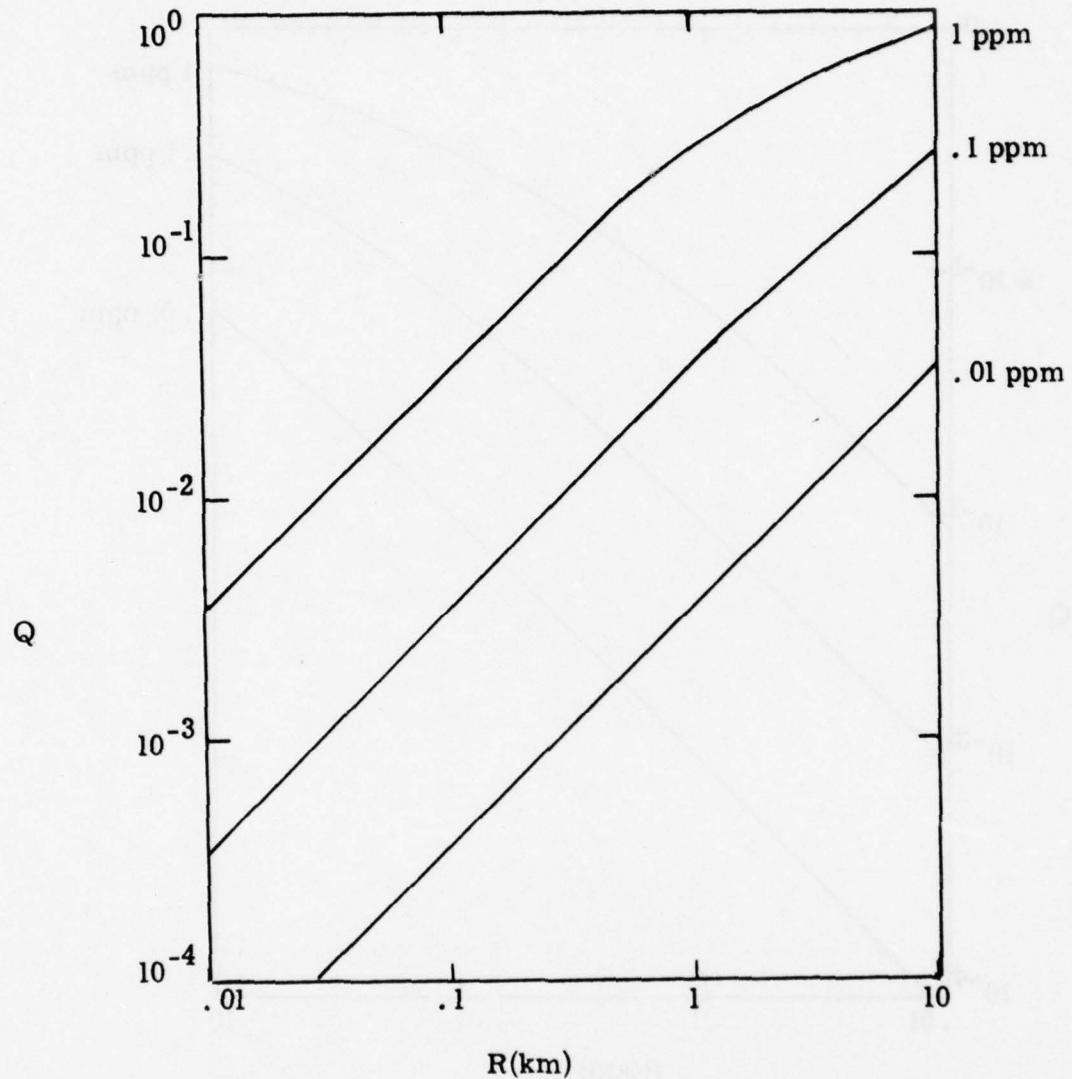


Figure 7.3.5-8f.  $Q$  for HCHO versus range for three levels of concentration.

7. 3. 5. 4o

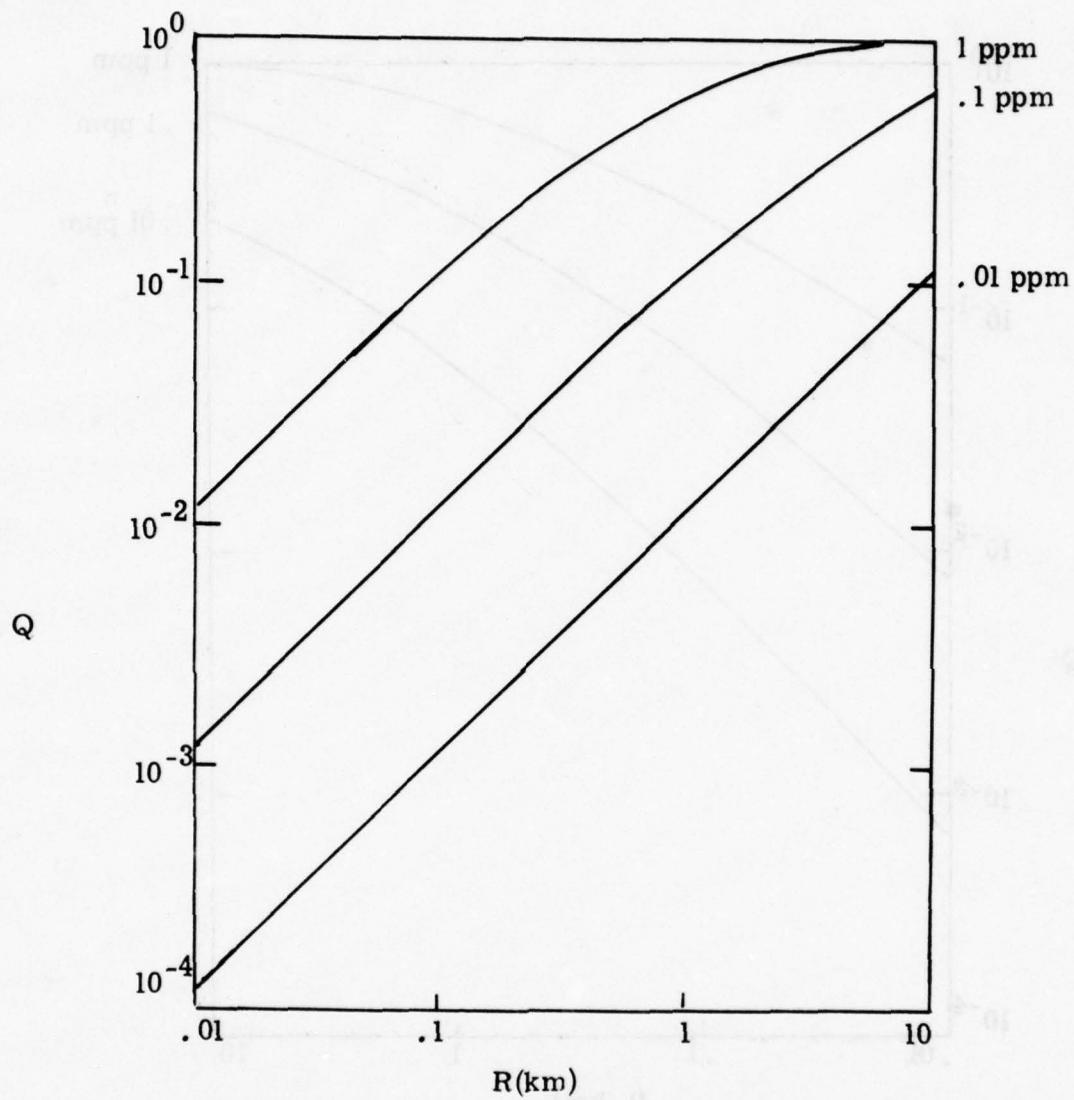


Figure 7. 3. 5-8g.  $Q$  for PAN versus range for three levels of concentration.

7. 3. 5. 4p

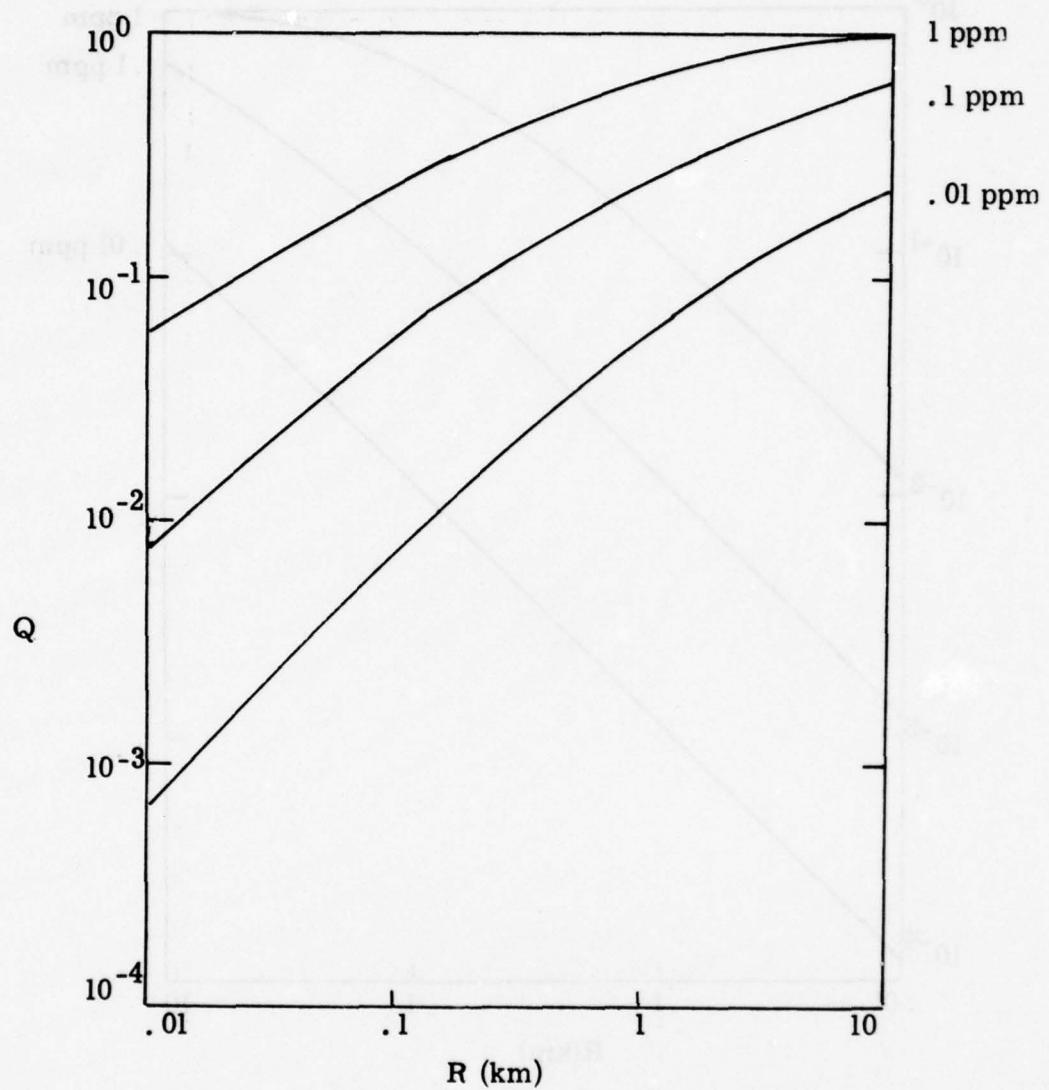


Figure 7. 3. 5-8h.  $Q$  for  $C_2H_4$  versus range for three levels of concentration.

7.3.5.4q

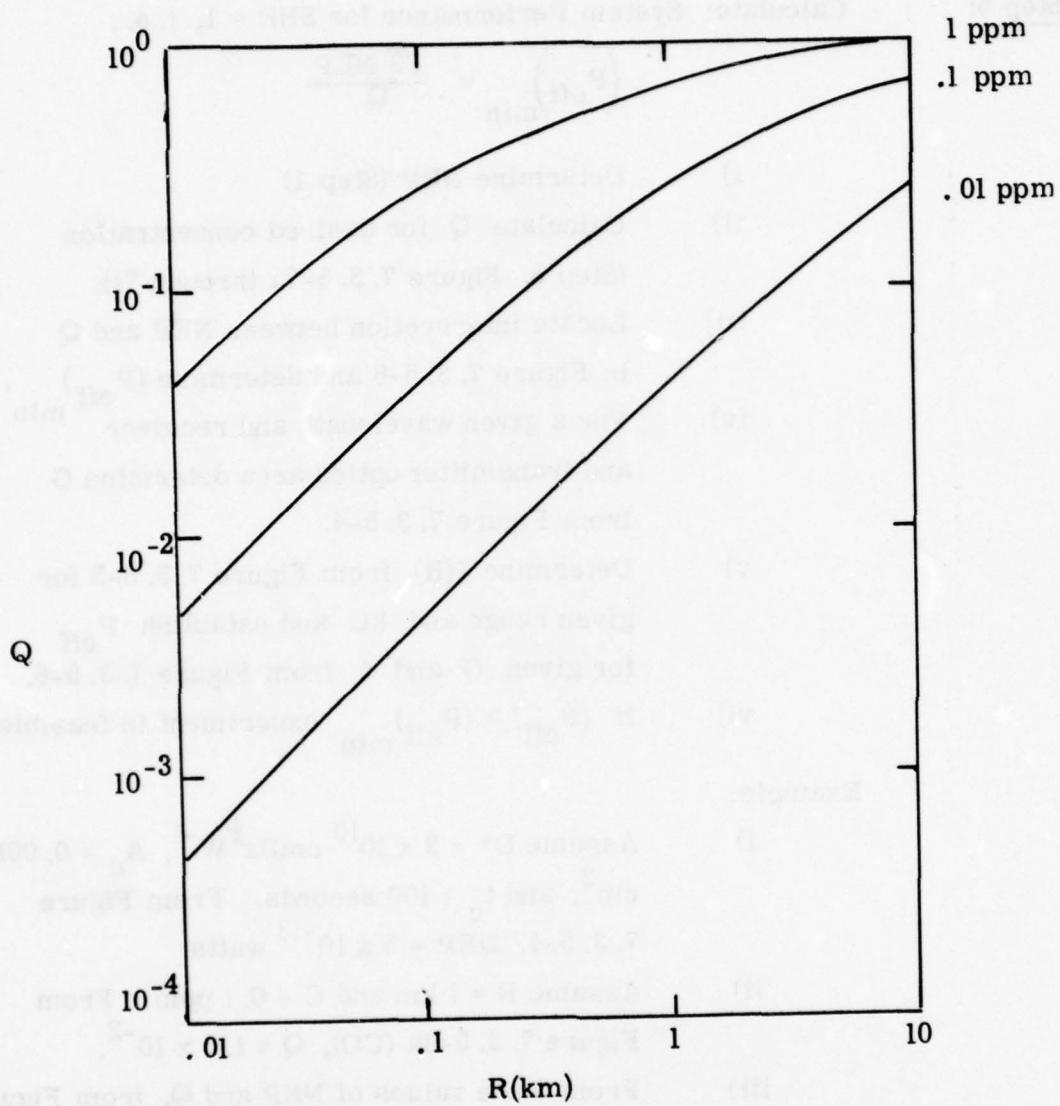


Figure 7.3.5-8i.  $Q$  for  $\text{C}_6\text{H}_6$  versus range for three levels of concentration.

Step 6:

Calculate: System Performance for SNR = 1, i.e.,

$$(P_{\text{eff}})_{\min} = \frac{\sqrt{2} \text{ NEP}}{Q}$$

- i) Determine NEP (Step 1)
- ii) Calculate Q for desired concentration (Step 5, Figure 7.3.5-7a through 7i).
- iii) Locate intersection between NEP and Q in Figure 7.3.5-8 and determine  $(P_{\text{eff}})_{\min}$ .
- iv) For a given wavelength and receiver and transmitter optics area determine G from Figure 7.3.5-4.
- v) Determine  $\xi(R)$  from Figure 7.3.5-5 for given range and kC and establish  $P_{\text{eff}}$  for given G and  $\xi$  from Figure 7.3.5-6.
- vi) If  $(P_{\text{eff}}) > (P_{\text{eff}})_{\min}$  experiment is feasible.

## Example:

- i) Assume  $D^* = 3 \times 10^{10} \text{ cmHz}^{-1} \text{ W}^{-1} \text{ cm}^2$ , and  $t_c = 100$  seconds. From Figure 7.3.5-4,  $\text{NEP} = 5 \times 10^{-13}$  watts.
- ii) Assume  $R = 1 \text{ km}$  and  $C = 0.1 \text{ ppm}$ . From Figure 7.3.5-8a (CO),  $Q = 1.5 \times 10^{-2}$ .
- iii) From these values of NEP and Q, from Figure 7.3.5-9  $(P_{\text{eff}})_{\min} = 6 \times 10^{-11}$ .
- iv) Assume  $\lambda = 4.7 \mu\text{m}$  and  $A_o = 10^3 \text{ cm}^2$  ( $A_o^2 = 10^6$ ). From Figure 7.3.5-5,  $G = 7.5 \times 10^4 \text{ Wcm}^2/\mu\text{m}$ .
- v) Having assumed above that  $R = 1 \text{ km}$  and  $C = 0.1 \text{ ppm}$   $k(\text{CO}) = 1.59$  and  $a = 0.02$  (tabulation, Step 5). Therefore,  $kC = 0.159$ . From Figure 7.3.5-6, curve 2, at  $R = 1 \text{ km}$ ,  $\xi(R) = 10^{-10} \text{ cm}^{-2}$ .

7. 3. 5. 4s

Having determined (above)  $G = 7.5 \times 10^4$ , if  $\Delta\lambda$  is assumed to be  $0.01 \mu\text{m}$ ,  $G_{\Delta\lambda}$  is  $7.5 \times 10^2$ . From Figure 7.3.5-7 for  $G_{\Delta\lambda} = 7.5 \times 10^2$  and  $\xi(R) = 10^{-10}$ ,  $P_{\text{eff}}$  is  $7 \times 10^{-8}$  watts.

- vi) Since  $P_{\text{eff}}$  ( $7 \times 10^{-8}$  watts) is greater than  $(P_{\text{eff}})_{\text{min}}$  ( $6 \times 10^{-11}$  watts), the experiment is feasible.

7.3.5.4t

$(P_{\text{eff}})_{\text{min}}$

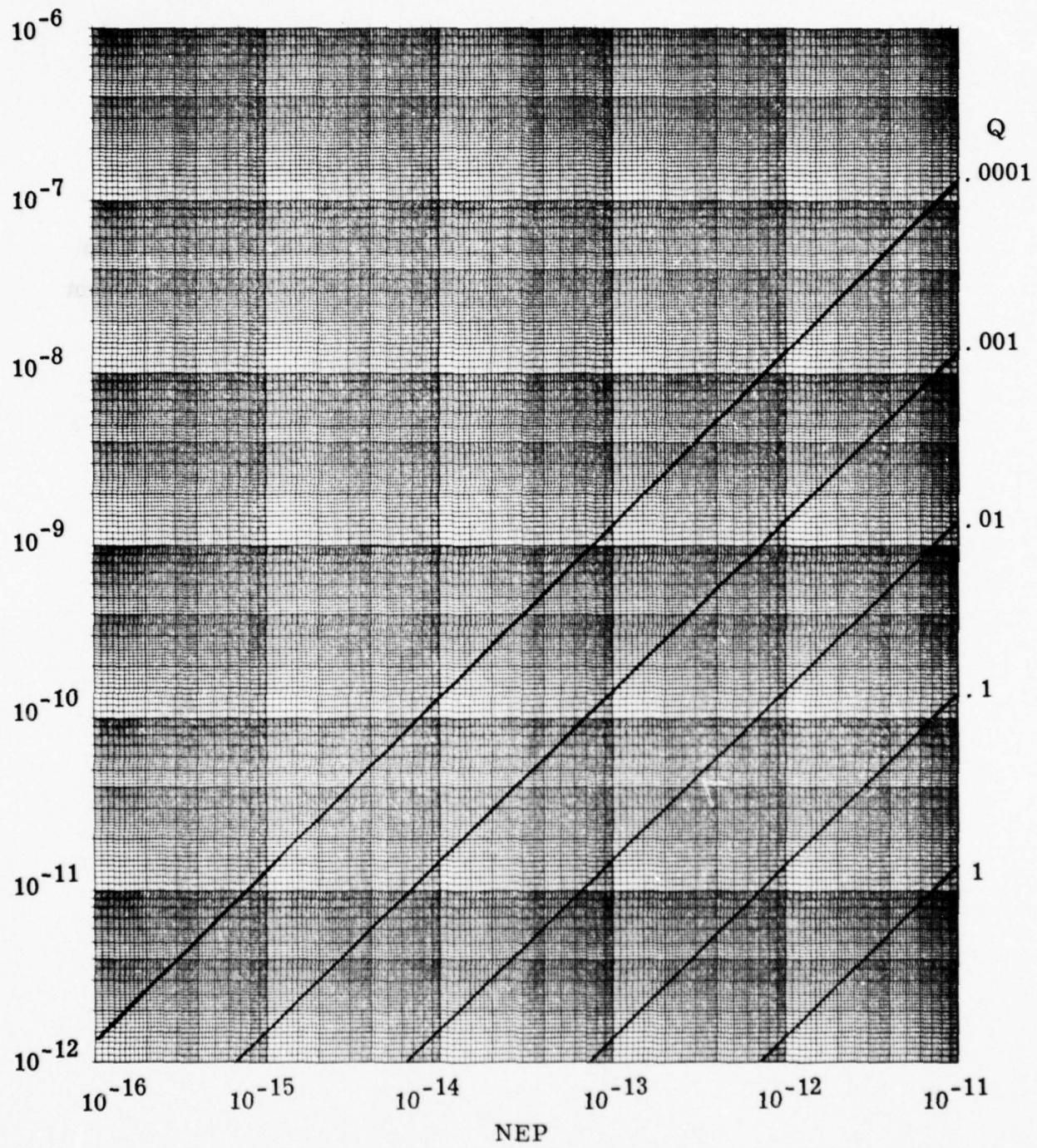


Figure 7.3.5-9.  $(P_{\text{eff}})_{\text{min}}$  versus NEP for different values of  $Q$ .

#### 7.3.5.5 Special Performance Requirements

The general requirements applicable to all remote monitors were described in Section 7.1.1, and special requirements applicable to all pollutants were described in Sections 7.2.1.5, 7.2.2.5 and 7.2.3.5.

#### 7.3.5.6 Data Analysis Procedure

In general, an analog recording of the scanning spectrophotometer is obtained such as the actual field data shown in Figure 7.3.5-10.

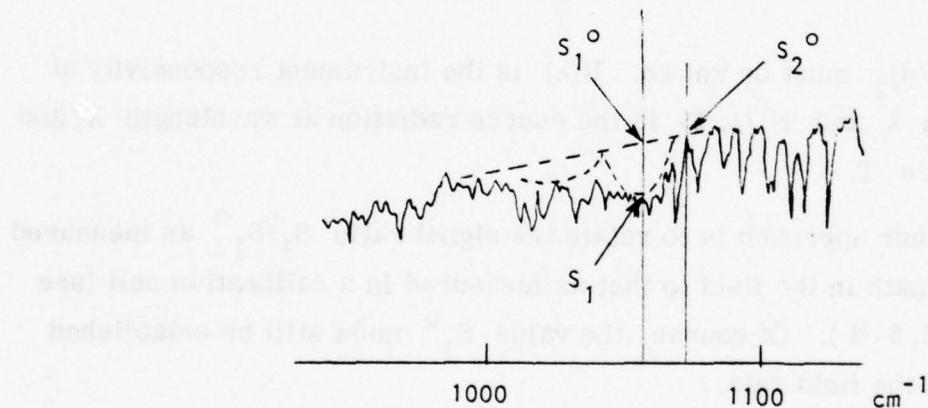


Figure 7.3.5-10. Analog recording over long-path through polluted atmosphere using a blackbody source as transmitter.

The concentration is implicitly determined through the ratio of the two signals  $S_1$  (the attenuated signal  $S_1^\circ$  (the non-attenuated signal), i. e.,

$$(W/d)_1 = n S_1^\circ / S_1$$

### 7.3.5.6b

where

$$W/d = k C R (1 + kCR/4a)^{-1/2}$$

Since  $S_1^0$  cannot be measured directly, it must be related to a spectral region where there is a known amount of absorption due to the natural species ( $H_2O$ ,  $CO_2$ , etc.). This relationship is given by

$$S_1^0 = \frac{N^0(\lambda_1, T)}{N^0(\lambda_2, T)} \frac{R(\lambda_1)}{R(\lambda_2)} e^{-(W/d)_2} S_2^0$$

where  $(W/d)_2$  must be known,  $R(\lambda)$  is the instrument responsivity at wavelength  $\lambda$  and  $N^0(\lambda, T)$  is the source radiation at wavelength  $\lambda$  and temperature  $T$ .

Another approach is to relate the signal ratio  $S_1/S_1^0$  as measured over long-path in the field to that as measured in a calibration cell (see Figure 7.3.5-11). Of course, the value  $S_1^0$  must still be established reliably in the field data.

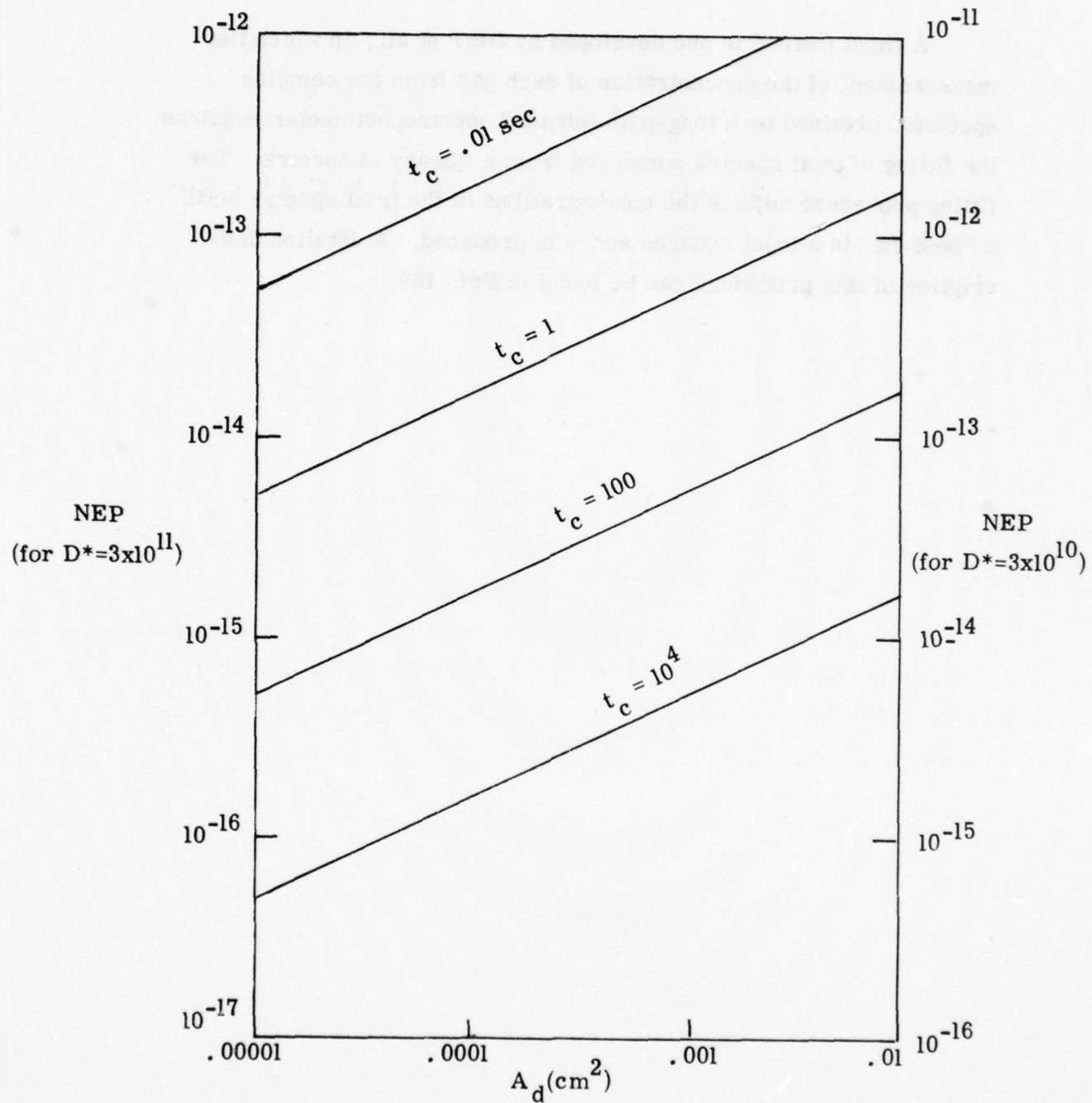


Figure 7.3.5-4 NEP versus  $A_d$  for Different Values of Integration Times, Assuming  $D^* = 3 \times 10^{10}$   $\text{cmHz}^{\frac{1}{2}} \text{W}^{-1}$  (right) and  $3 \times 10^{11}$   $\text{cmHz}^{\frac{1}{2}} \text{W}^{-1}$  (left).

7. 3. 5. 6d

A third method is one developed by Derr et al., in which the measurement of the concentration of each gas from the complex spectrum obtained by a long-path infrared spectrophotometer requires the fitting of trial spectra composed from a library of spectra. The fitting procedure adjusts the concentrations of the trial spectra until a "best-fit" in a least squares sense is produced. A detailed description of this procedure can be found in Ref. 169.

### 7.3.6 IR Long-Path with Broadband Source (bi-static) Using Fourier Transform Spectrometer Receiver

#### 7.3.6.1 Principle of Operation

The infrared long-path transmission technique is used to obtain line averaged concentrations of all gaseous pollutants of interest to NAAQS. A beam from a broadband source is emitted and the transmitted signals are recorded by the Fourier Transform Spectrometer (FTS) receiver as a function of wavelength. By differencing the signals on and off the pollutant lines, the average absorption of the pollutants over the line-of-sight can be determined. The concentration of the pollutant is proportional to the logarithm of the transmission. The proportionality factor is the absorption coefficient which must be known.

#### 7.3.6.2 System Description

The system consists of a broad band source, such as a blackbody, transmitting optics, remote collecting optics, the FTS, electronics and data display. Thus the system is essentially the same as that described in Section 7.3.5.2 except that the dispersive receiver is replaced with the non-dispersive FTS, and the chopper is not needed at the source. A typical system is shown schematically in Figure 7.3.6-1. Details of a typical FTS are given in Figure 7.3.6-2.

#### 7.3.6.3 System Parameters

##### Commercially available broad band source

Blackbody ( $\sim 1200$  K) uncooled

( $\sim 1500$  K) forced air cooled

( $\sim 1800$  K) water cooled

Nernst glower, an electrically heated cylinder of zirconium and yttrium oxide. [272, 273].

7. 3. 6. 3b

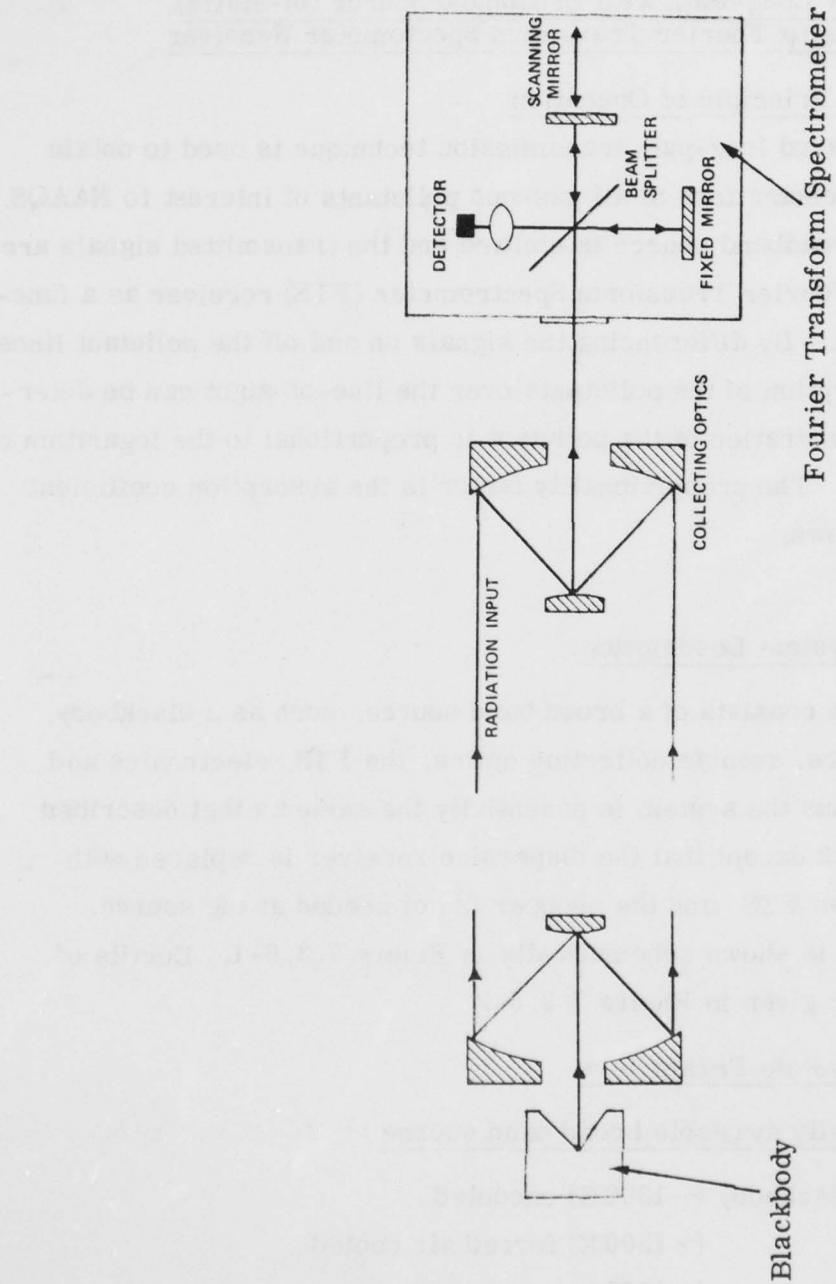


Figure 7.3.6-1. Schematic of IR Long-Path System.

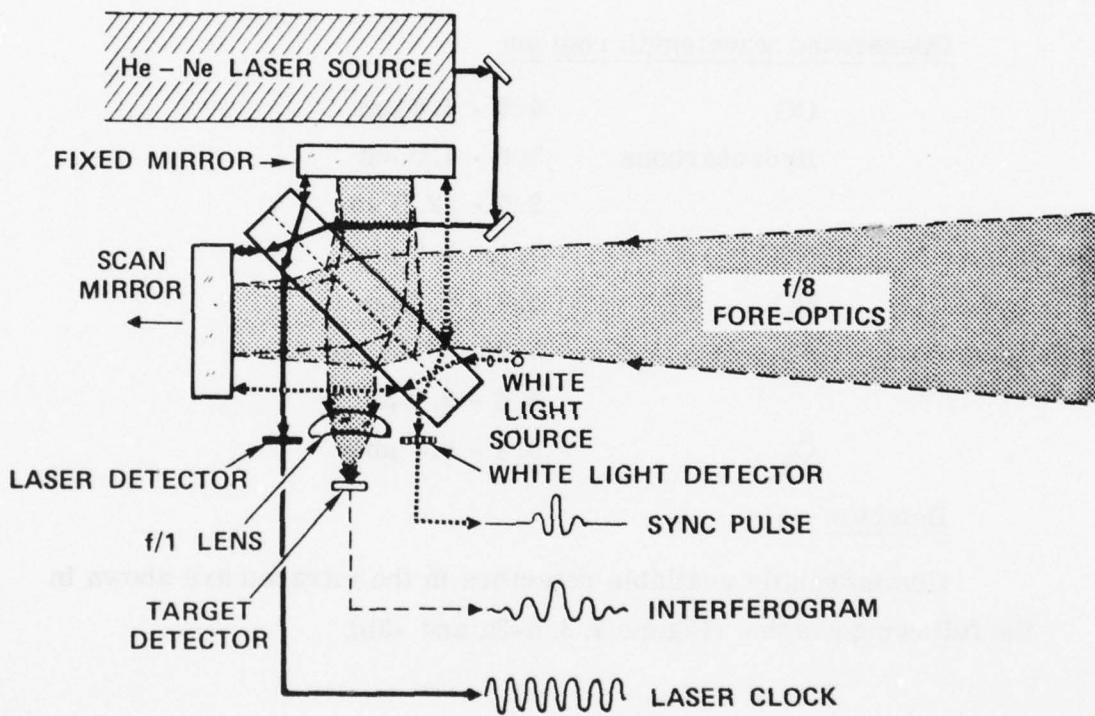


Figure 7.3.6-2. Optical Lay-Out of Fourier Transform Spectrometer.

### 7. 3. 6. 3d

#### Commercially available Fourier Transform Spectrometer

Various FTS with and without on-line processors are available from two or three manufacturers. They may cover any part or all of the thermal infrared region depending on the choice of optical components, e.g. windows, beamsplitter, and detector, in the FTS.

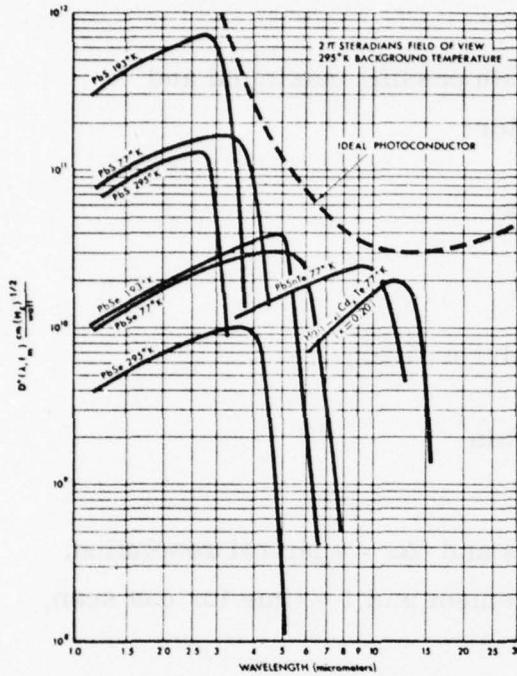
#### Operational wavelength regions

CO	4.5 - 4.8 $\mu\text{m}$
Hydrocarbons	3.0 - 4.0 $\mu\text{m}$
	9.5 - 12.0 $\mu\text{m}$
NO	5.1 - 5.5 $\mu\text{m}$
NO <sub>2</sub>	3.3 - 3.6 $\mu\text{m}$
SO <sub>2</sub>	3.95 - 4.05 $\mu\text{m}$
	8.4 - 9.0 $\mu\text{m}$
O <sub>3</sub>	9.4 - 9.8 $\mu\text{m}$

#### Detector

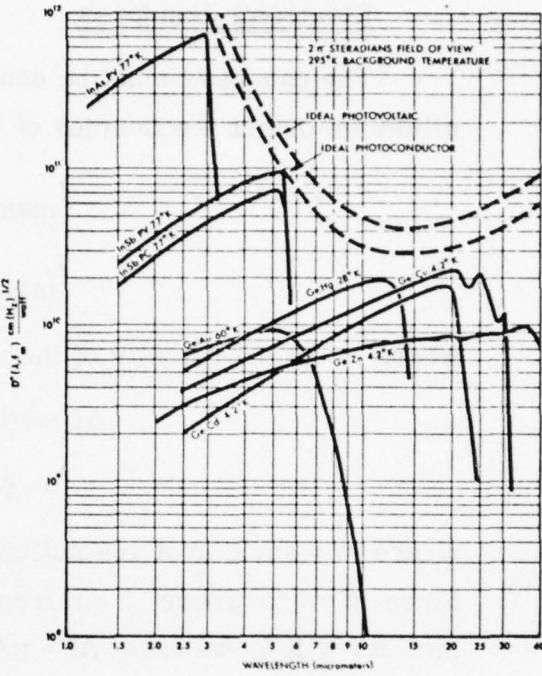
Commercially available detectors in the infrared are shown in the following graphs (Figure 7. 3. 6-3a and -3b).

### 7.3.6.3e



SPECTRAL DETECTIVITIES FOR ABOVE AVERAGE DETECTORS FABRICATED BY SRRC.  
A REDUCTION IN BACKGROUND PHOTON FLUX PRODUCES HIGHER DETECTIVITIES

Figure 7.3.6-3a



SPECTRAL DETECTIVITIES FOR ABOVE AVERAGE DETECTORS FABRICATED BY SRRC.  
A REDUCTION IN BACKGROUND PHOTON FLUX PRODUCES HIGHER DETECTIVITIES

Figure 7.3.6-3b

### Optics

Collecting Aperture

$$A_o$$

Solid Angle

$$\Omega_o$$

Optical Efficiency

$$\eta_{\text{opt}}$$

Detector Optics

$$A_d \Omega_d (= A_o \Omega_o)$$

It should be noted that, for the FTS,  $\Omega_o$  is related to the spectral resolution  $\Delta\nu$ , by

$$(\Omega_o)_{\text{max}} = 2\pi \frac{\Delta\nu}{\nu_{\text{max}}}$$

These optical parameters are variables that must be chosen to fulfill the operational requirements (shown in the following).

### Electronic Bandpass

The bandpass must be consistent with passing maximum and minimum output frequencies of the detector:

$$f_{\max} = v \nu_{\max}$$

$$f_{\min} = v \nu_{\min}$$

where  $v$  is the velocity of the moving mirror; i.e.,

$$\begin{aligned}\Delta f &= v(\nu_{\max} - \nu_{\min}) \\ &= v\Delta\nu n\end{aligned}$$

where  $n$  = number of resolution elements and  $\Delta\nu$  = spectral resolution. Since  $v = \delta/t$  where  $\delta$  = mirror displacement and  $t$  = time for one scan, and  $\Delta\nu = 1/\delta$ , we have  $\Delta f = n/t$ .

### 7. 3. 6. 4 Theoretical Performance Prediction

Based upon the selected system parameters, the performance can be predicted for a detector-noise-limited system. The procedure follows exactly that given for the IR long path system with a dispersive receiver described in Section 7. 2. 6. 4.

There are two main advantages<sup>(268)</sup> for the FTS system compared to the dispersive system, assuming that the transmitting and collecting optics are optimally designed for each system. The first is Fellgett's advantage:

The signals from all spectral elements are recorded in parallel rather than sequentially as in the dispersive system. Thus for  $n$  resolution elements the FTS records the spectrum  $n$  times faster than the dispersive spectrometer, or if each system takes the same time the SNR of the FTS is  $n^{\frac{1}{2}}$  times greater.

### 7. 3. 6. 4b

The second is Jacquinot's advantage:

The FTS has a larger etendue (throughput). The ratio of throughputs for the FTS and the grating spectrometer (GS) is given approximately by

$$\frac{A\Omega(FTS)}{A\Omega(GS)} = 2\pi \frac{F}{L}$$

where  $F$  is the focal length of the collimator and  $L$  is the slit height. This ratio is typically 100 to 200.

The signal-to-noise ratio for the determination of the pollutant concentration is given by

$$SNR = \frac{\ln Q'}{dP \sqrt{(1/P)^2 + (1/P')^2}}$$

where

$$\ln Q' = \ln P/P'$$

$$P = G/R^2 e^{-(w/d)} {}_1 \Delta \lambda$$

$$P' = G/R^2 e^{-(w/d)} {}_2 \Delta \lambda$$

$$G = \eta A_t A_r N^0(\lambda, T)$$

$$w/d = kCR(1 + kCR/4a)^{-1/2}$$

$$dP = NEP = (A_d/4\tau)^{1/2}/D^*$$

The SNR may be simplified, i.e.,

$$SNR = \frac{Q P_{eff}}{\sqrt{2} NEP}$$

where

$$Q = (w/d)_2 - (w/d)_1$$

$$P_{\text{eff}} = G \xi(R) \Delta \lambda$$

$$\xi(R) = R^{-2} e^{-(w/d)}$$

In the following a stepwise description for the calculation of SNR is given:

Step 1: Calculate: NEP

Assume:  $D^* = 3 \times 10^{10} \text{ cm Hz}^{1/2} \text{W}^{-1}$  (representative for MWIR to LWIR)

$D^* = 3 \times 10^{11} \text{ cm Hz}^{1/2} \text{W}^{-1}$  (representative for SWIR)

Result: Plot in Figure 7.3.6-4 shows NEP versus  $A_d$  for different  $\Delta f$ . ( $\Delta f = 1/4 t_c$ )

Step 2: Calculate: G

Assume:  $T = 1600 \text{ K}$

$$\eta = .1$$

Result: Plot in Figure 7.3.6-5 shows  $G$  versus  $\lambda$  for different typical values of  $A_0$

Step 3: Calculate:  $\xi(R) = R^{-2} e^{-(w/d)}$

Assume:  $kC = 0, .3, 1, 3 \text{ km}^{-1}$

Result: Plot in Figure 7.3.6-6 shows  $\xi(R)$  versus  $R$  for the above values of  $kC$  and six values of  $a$ .

Curve (1)	$kC = 0$
(2)	$kC = .3, a = .01$
(3)	$kC = 1, a = .01$
(4)	$kC = 3, a = .01$
(5)	$kC = .3, a = 10$
(6)	$kC = 1, a = 10$
(7)	$kC = 3, a = 10$

7.3.6.4d

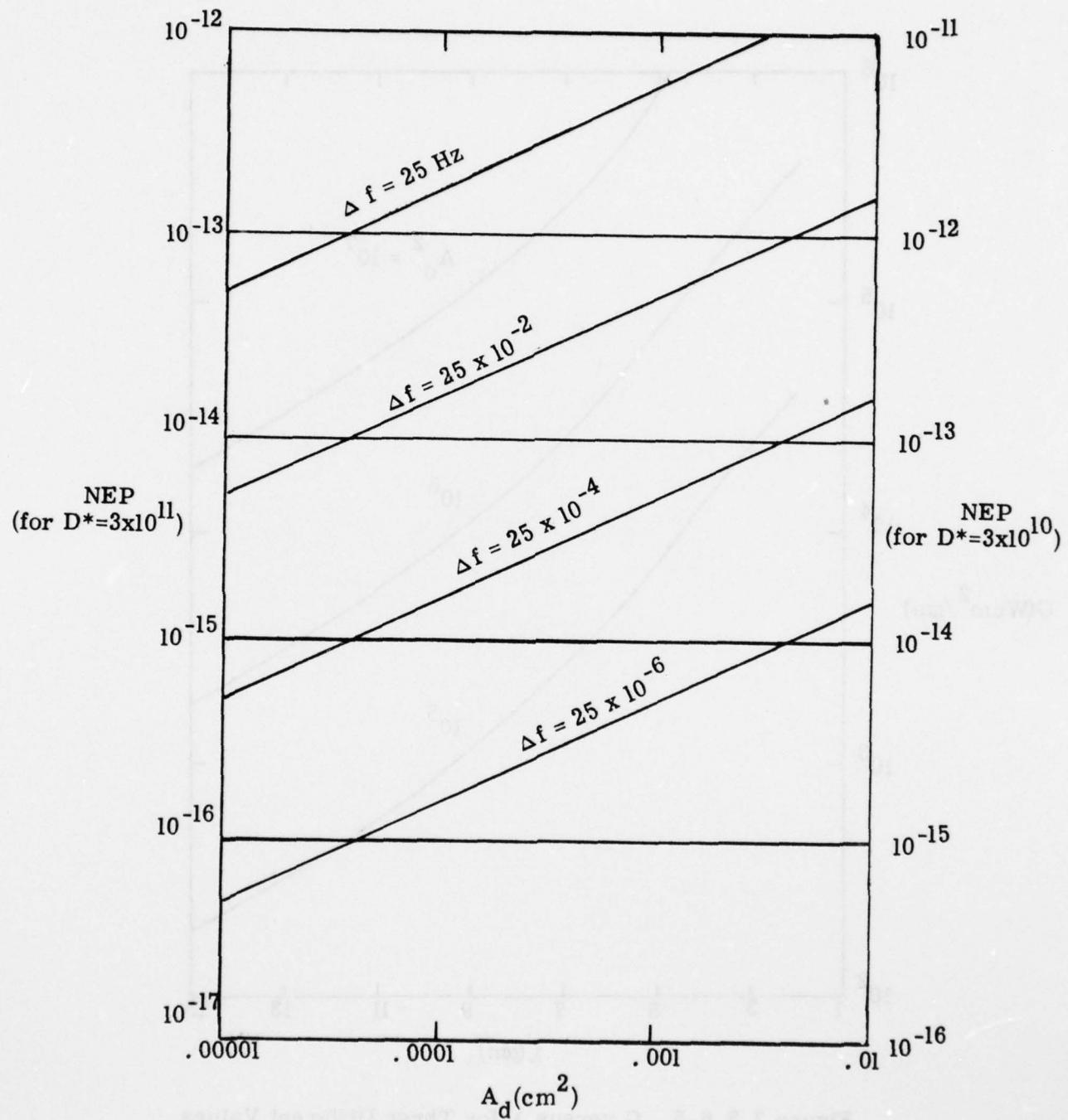


Figure 7.3.6-4. NEP Versus  $A_d$  for Different Electronic Bandpasses. Assuming  $D^* = 3 \times 10^{10} \text{ cm Hz}^{\frac{1}{2}} \text{W}^{-\frac{1}{2}}$ , and  $3 \times 10^{11} \text{ cm Hz}^{\frac{1}{2}} \text{W}^{-\frac{1}{2}}$ .

7.3.6.4e

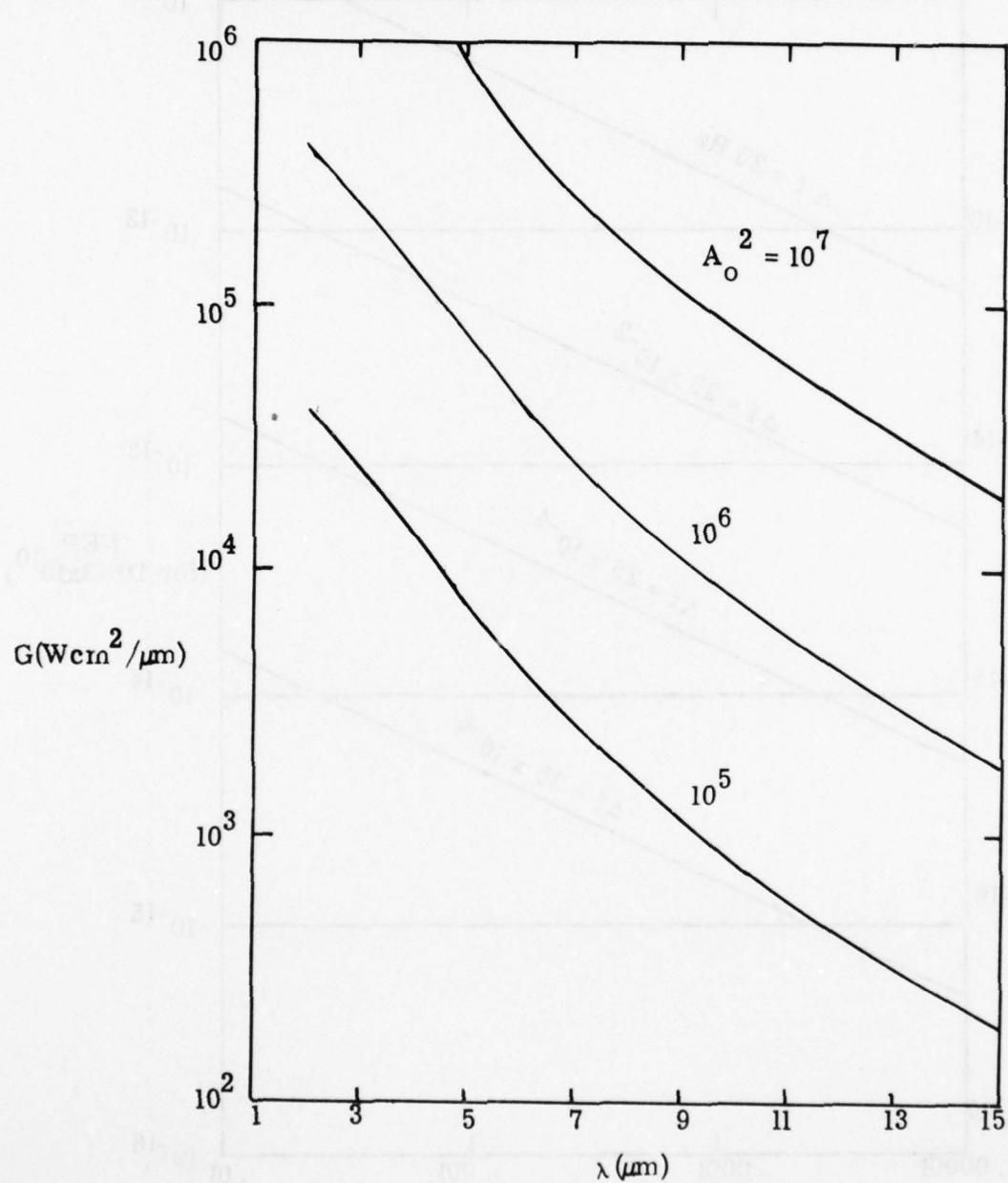
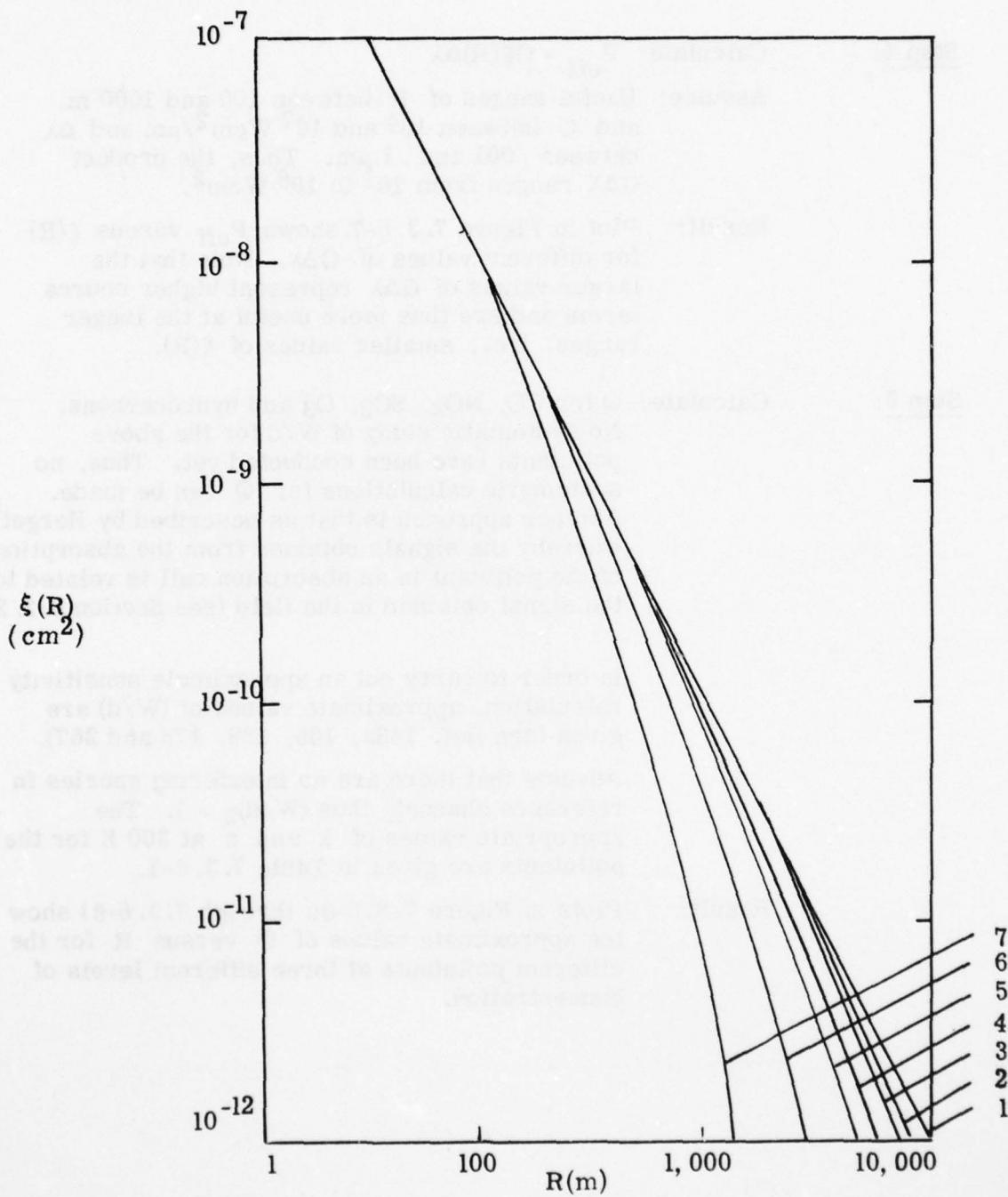


Figure 7.3.6-5.  $G$  versus  $\lambda$  for Three Different Values of  $(A_0^2)$ .



Figure

Figure 7.2.6-6.  $\xi(R)$  versus  $R$  for Different Values of  $kC$  and  $a$ : Curve (1)  $kC = 0$ ;

Curve (2)  $kC = .3, a = .01$

(3)  $kC = 1, a = .01$

(4)  $kC = 3, a = .01$

(5)  $kC = .3, a = 10$

(6)  $kC = 1, a = 10$

(7)  $kC = 3, a = 10$

Step 4:

Calculate:  $P_{\text{eff}} = G\xi(R)\Delta\lambda$

Assume: Useful ranges of  $R$  between 100 and 1000 m, and  $G$  between  $10^4$  and  $10^7 \text{ Wcm}^2/\mu\text{m}$  and  $\Delta\lambda$  between .001 and .1  $\mu\text{m}$ . Thus, the product  $G\Delta\lambda$  ranges from  $10^1$  to  $10^6 \text{ Wcm}^2$ .

Result: Plot in Figure 7.3.6-7 shows  $P_{\text{eff}}$  versus  $\xi(R)$  for different values of  $G\Delta\lambda$ . Note that the larger values of  $G\Delta\lambda$  represent higher source terms and are thus more useful at the longer ranges, i.e., smaller values of  $\xi(R)$ .

Step 5:

Calculate:  $Q$  for CO, NO<sub>x</sub>, SO<sub>2</sub>, O<sub>3</sub> and hydrocarbons. No systematic study of  $W/d$  for the above pollutants have been conducted yet. Thus, no systematic calculations for  $Q$  can be made. Another approach is that as described by Herget<sup>(246)</sup>, whereby the signals obtained from the absorption of the pollutant in an absorption cell is related to the signal obtained in the field (see Section 5.3.2.2).

In order to carry out an approximate sensitivity calculation, approximate values of  $(W/d)$  are given (see Ref. 146a, 166, 169, 176 and 267).

Assume that there are no interfering species in reference channel, thus  $(W/d)_2 = 1$ . The appropriate values of  $k$  and  $a$  at 300 K for the pollutants are given in Table 7.3.6-1.

## Result:

Plots in Figure 7.3.6-8a through 7.3.6-8i show the approximate values of  $Q$  versus  $R$  for the different pollutants at three different levels of concentration.

7. 3. 6. 4h

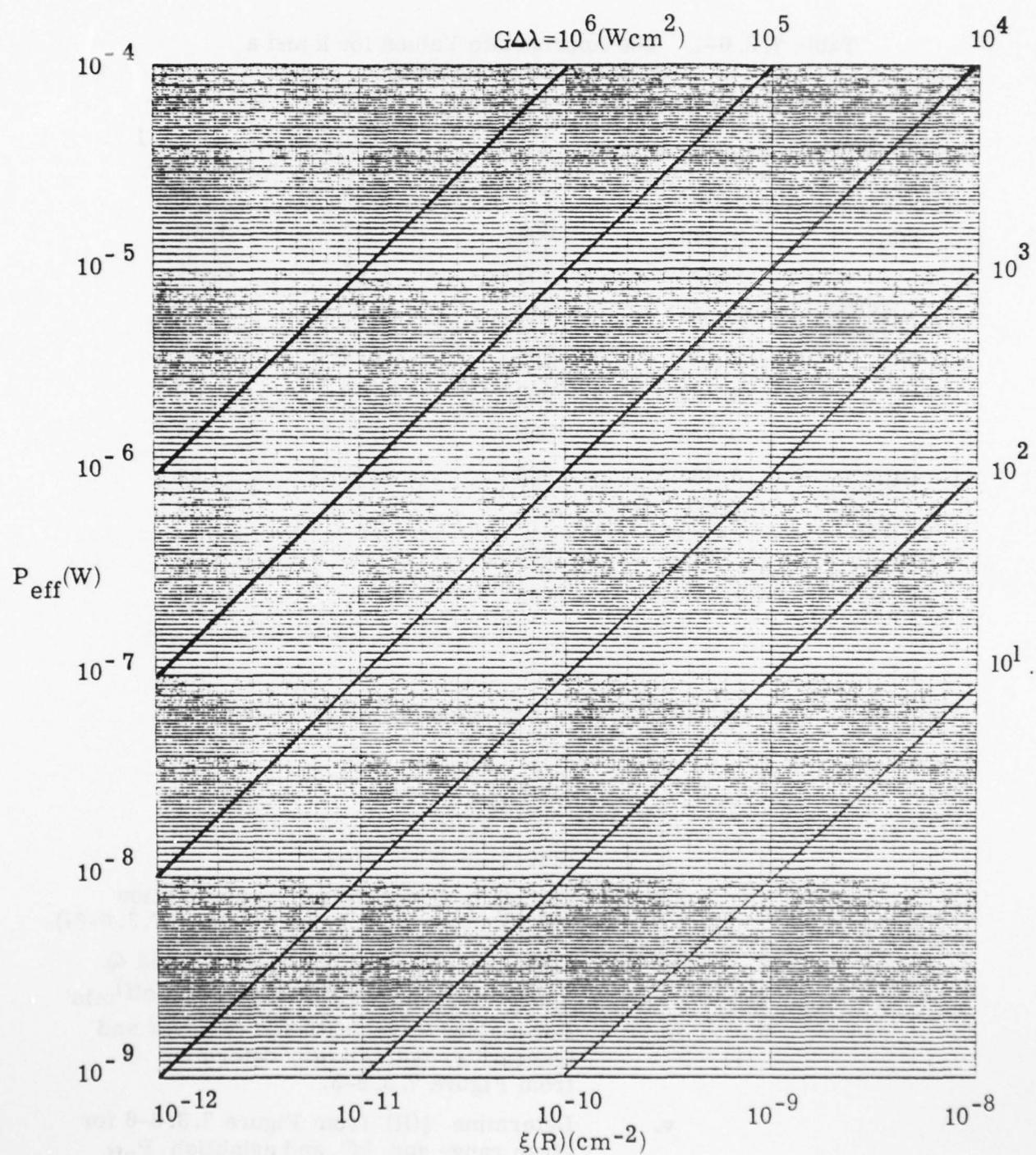


Figure 7. 3. 6-7.  $P_{\text{eff}}$  versus  $\xi(\text{R})$  for Different Values of  $G\Delta\lambda$ .

Table 7.3.6-1. The Appropriate Values for k and a<sub>o</sub> at 300 K for Pollutants.

Pollutant	$\lambda$ ( $\mu\text{m}$ )	$\Delta\lambda$ ( $\mu\text{m}$ )	$k$ ( $\text{cm atm}$ ) <sup>-1</sup>	$a_o$ ( $\text{atm}$ ) <sup>-1</sup>
CO	4.551	.010	1.59	.02
$\text{SO}_2$	3.996	.008	.25	1.39
	8.639	.037	1.08	2.44
NO	5.202	.014	1.01	.08
$\text{NO}_2$	3.422	.006	1.20	.93
$\text{O}_3$	9.722	.060	9.15	.05
	0.530	.050	7.90	.05
HCHO	3.433	.006	3.52	.55
$\text{C}_2\text{H}_4$	10.563	.050	73.0	.03
PAN	12.20	.065	12.4	.5
$\text{C}_6\text{H}_6$	3.287	.011	46.4	.08

Step 6: Calculate: System Performance for SNR = 1, i.e.,

$$\left( P_{\text{eff}} \right)_{\min} = \frac{\sqrt{2} \text{ NEP}}{Q}$$

- i. Determine NEP (Step 1)
- ii. Calculate Q for desired concentration (Step 5, Figures 7.3.6-8a through 7.3.6-8i).
- iii. Locate intersection between NEP and Q in Figure 7.3.6-10 and determine  $(P_{\text{eff}})_{\min}$ .
- iv. For a given wavelength and receiver and transmitter optics area, determine G from Figure 7.3.6-5.
- v. Determine  $\xi(R)$  from Figure 7.3.6-6 for given range and kC and establish  $P_{\text{eff}}$  for given G and  $\xi$  from Figure 7.3.6-7.
- vi. If  $(P_{\text{eff}}) > (P_{\text{eff}})_{\min}$  experiment is feasible.

7. 3. 6. 4j

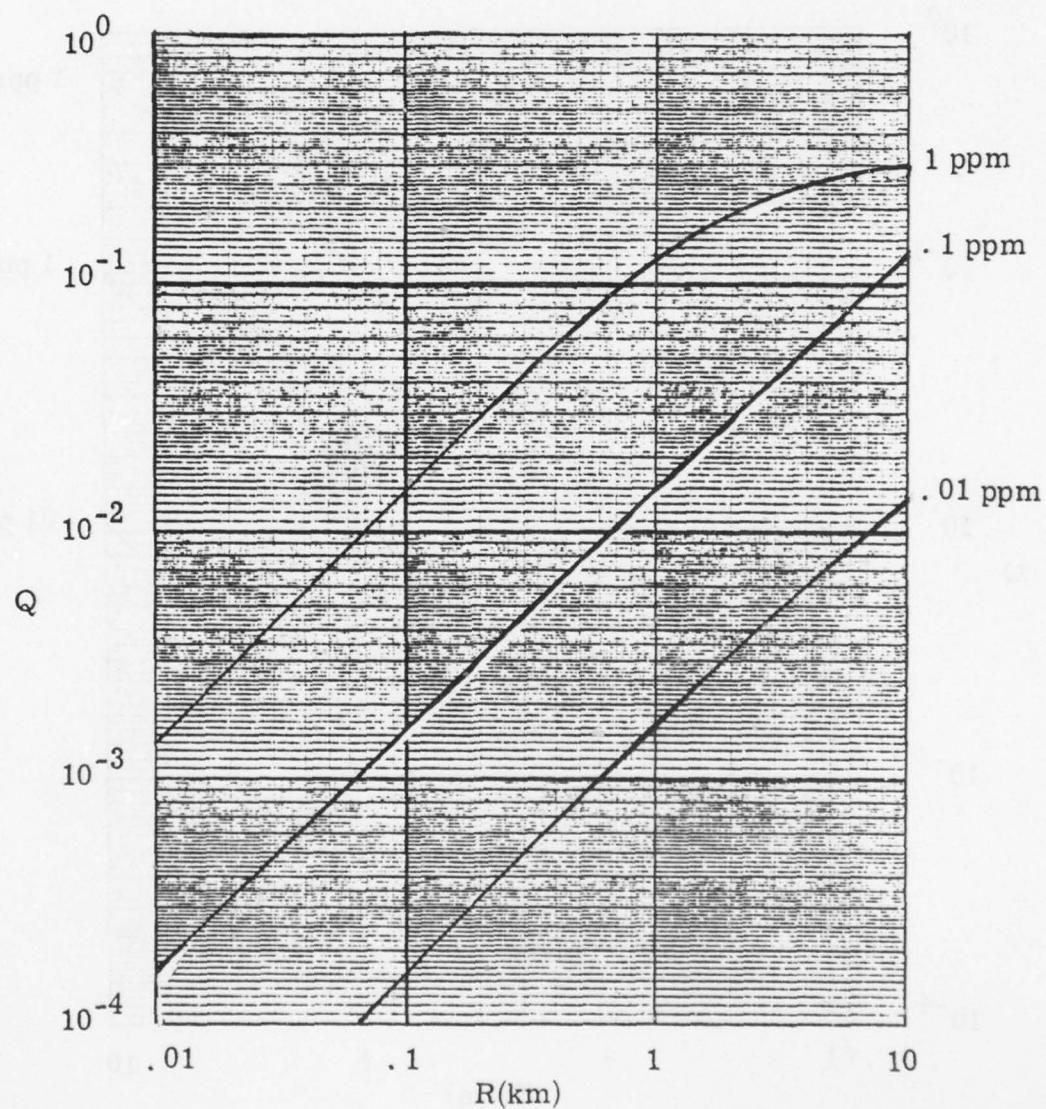


Figure 7.3.6-8a.  $Q$  for CO versus range for three levels of concentration.

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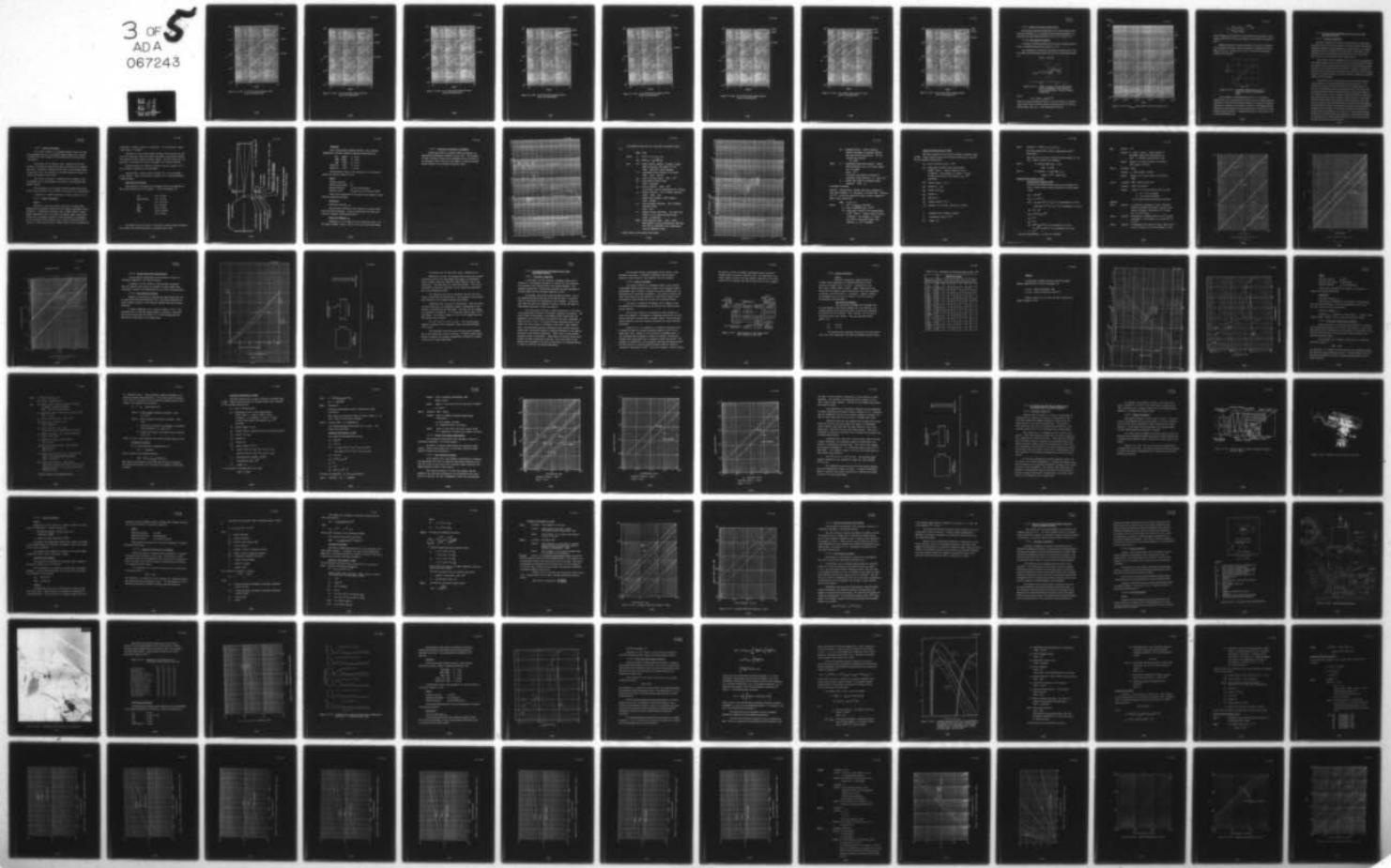
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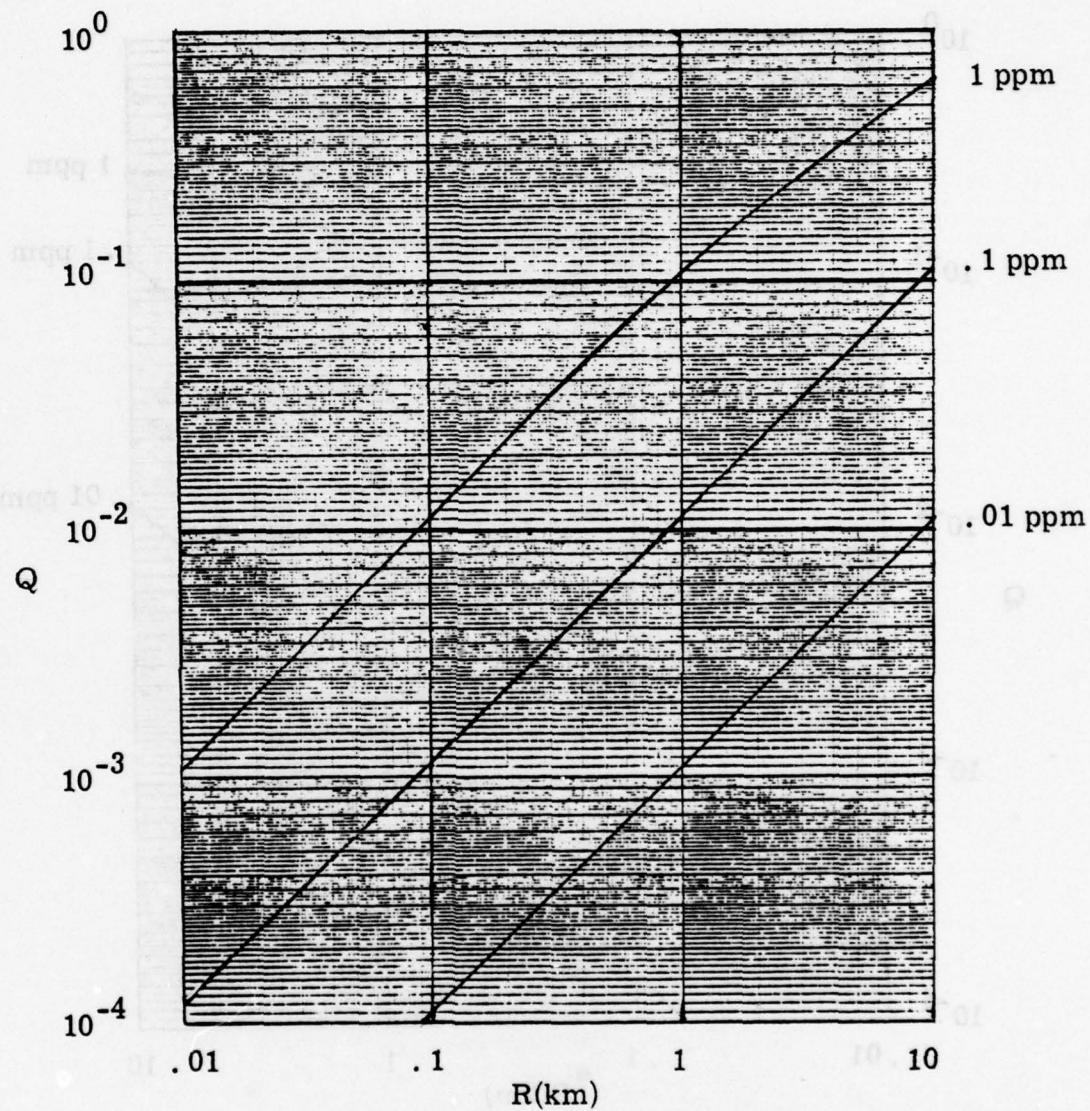


Figure 7. 3. 6-8b.  $Q$  for  $\text{SO}_2$  versus range for three levels of concentration.

7. 3. 6. 41

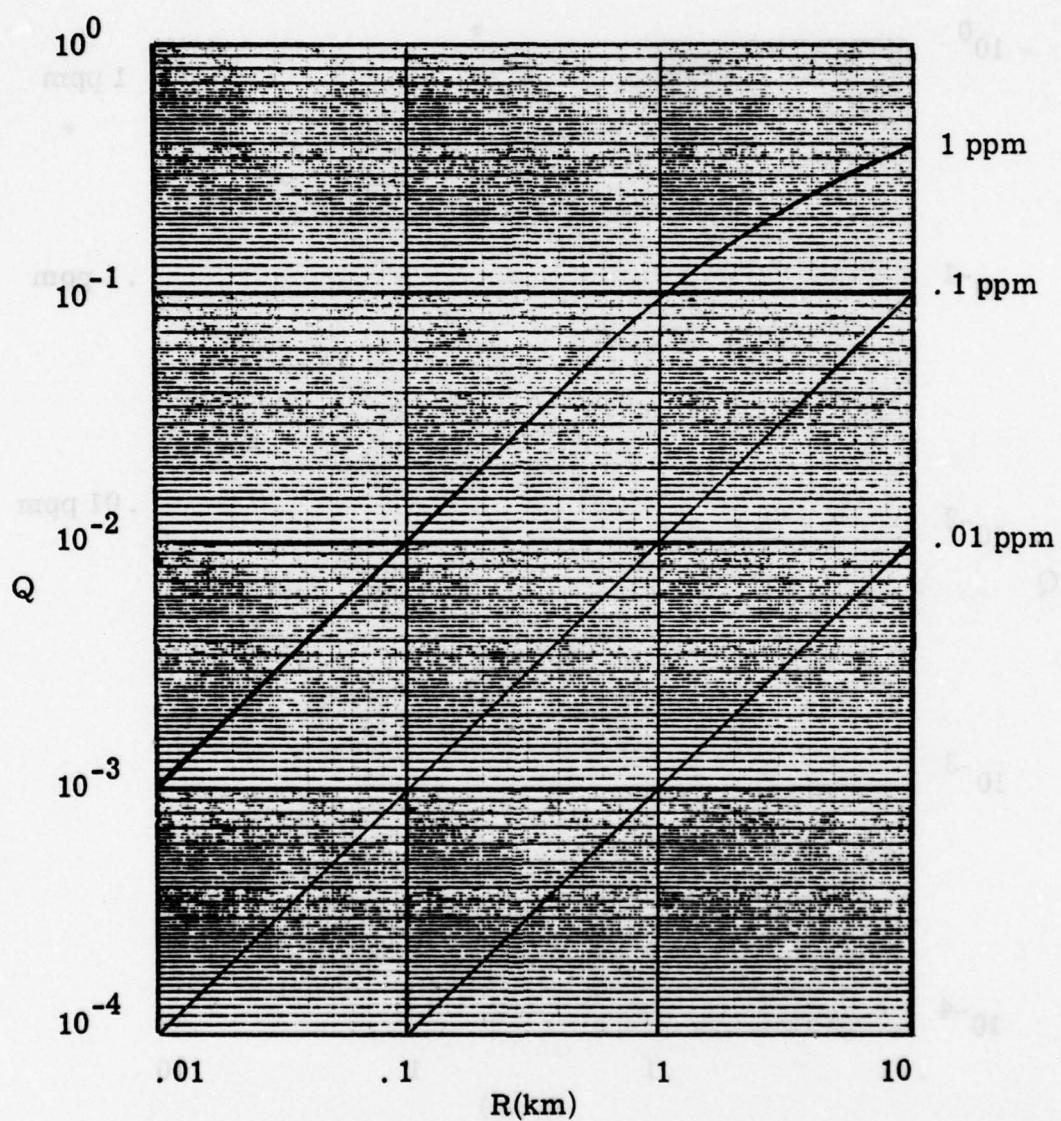


Figure 7. 3. 6-8c.  $Q$  for NO versus range for three levels of concentration.

7. 3. 6. 4m

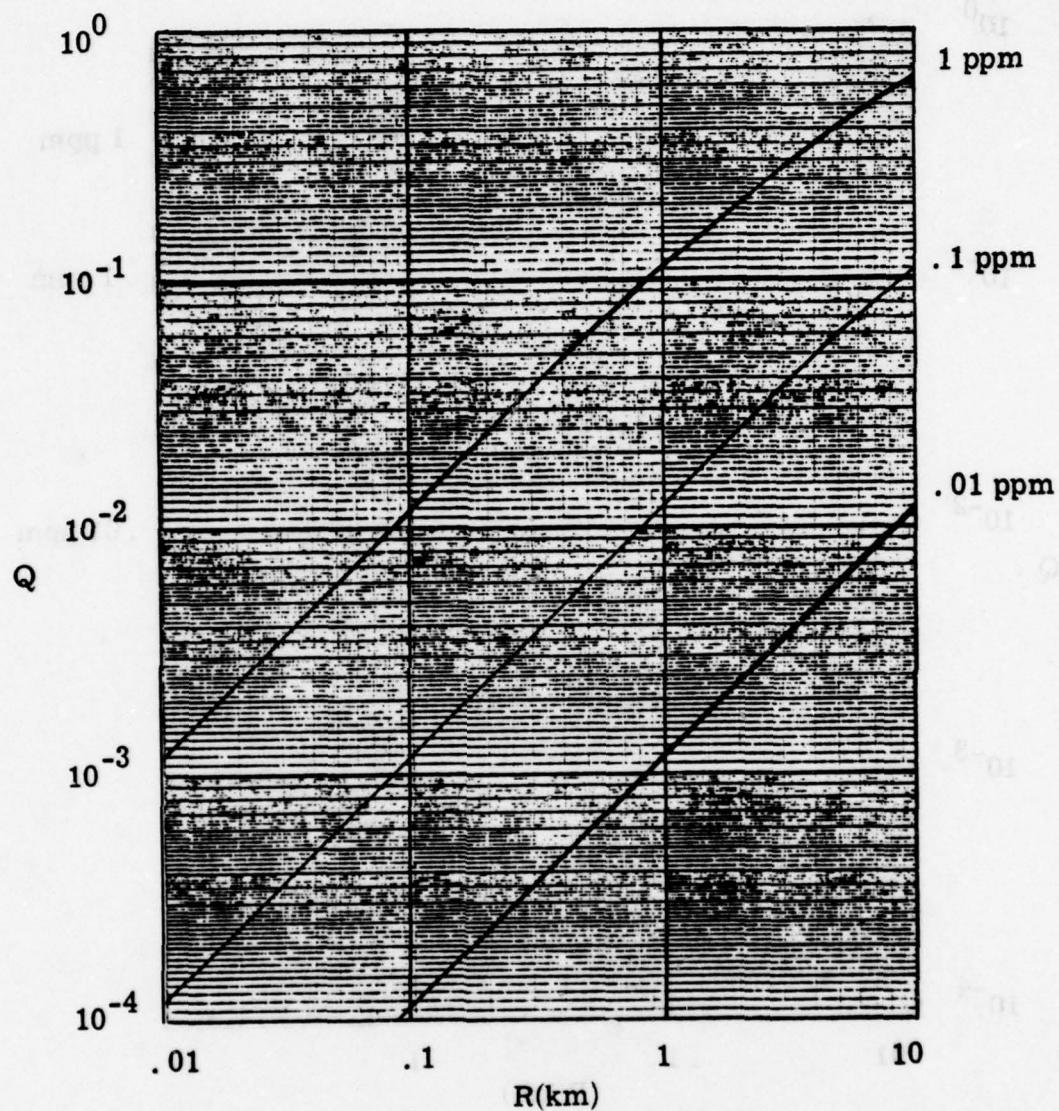


Figure 7. 3. 6-8d.  $Q$  for  $\text{NO}_2$  versus range for three levels of concentration.

7. 3. 6. 4n

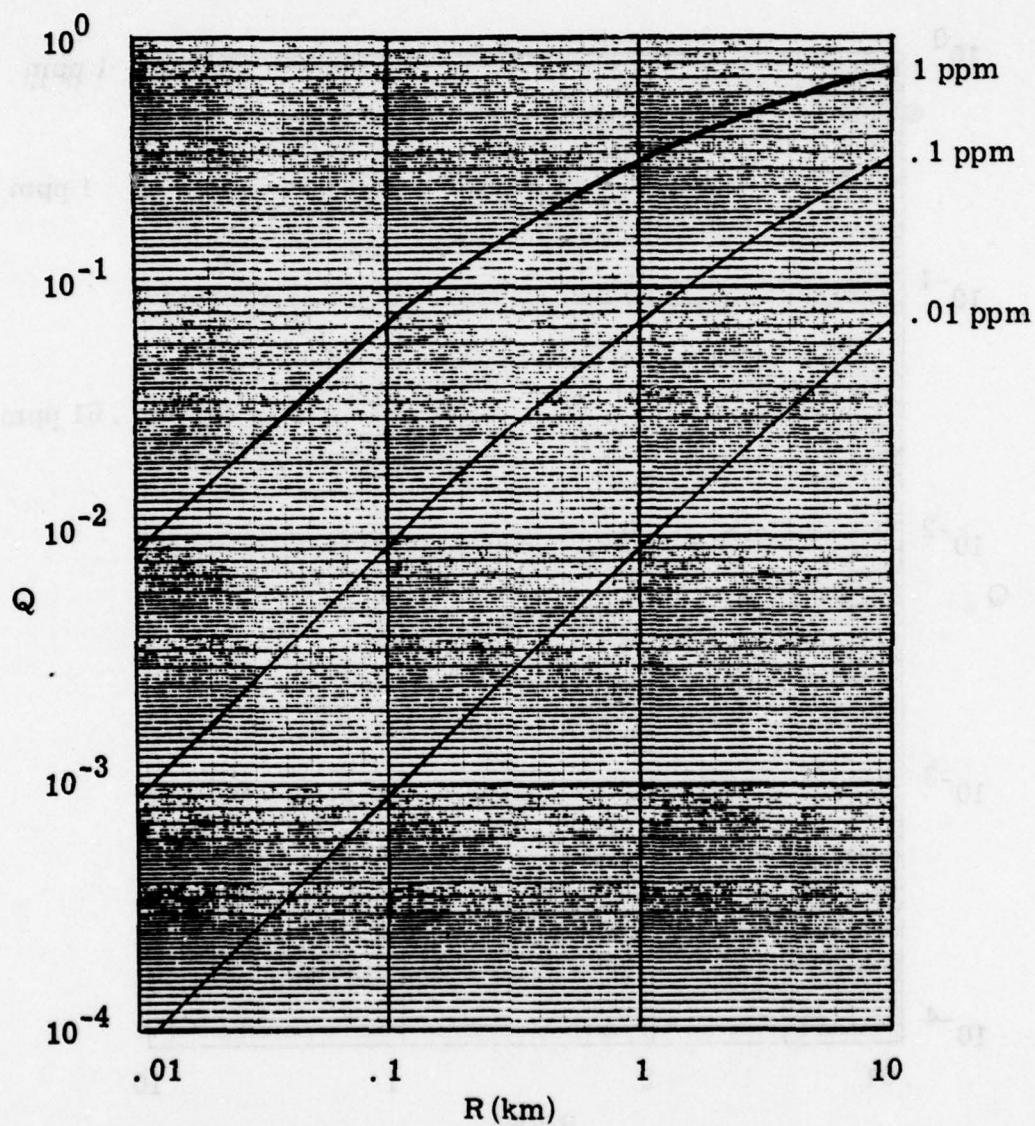


Figure 7. 3. 6-8e.  $Q$  for  $O_3$  versus range for three levels of concentration.

7. 3. 6. 4o

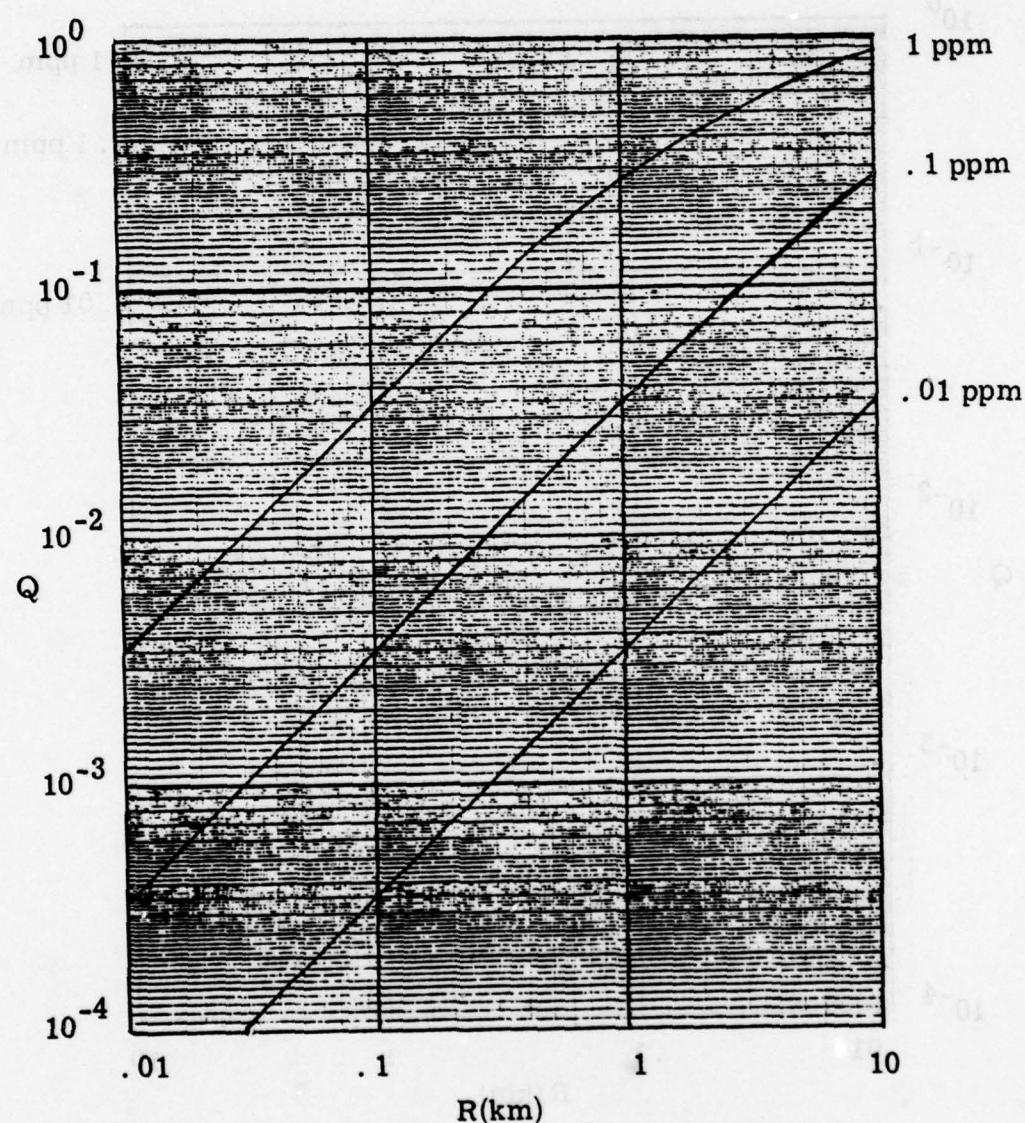


Figure 7. 3. 6-8f.  $Q$  for HCHO versus range for three levels of concentration.

7. 3. 6. 4p

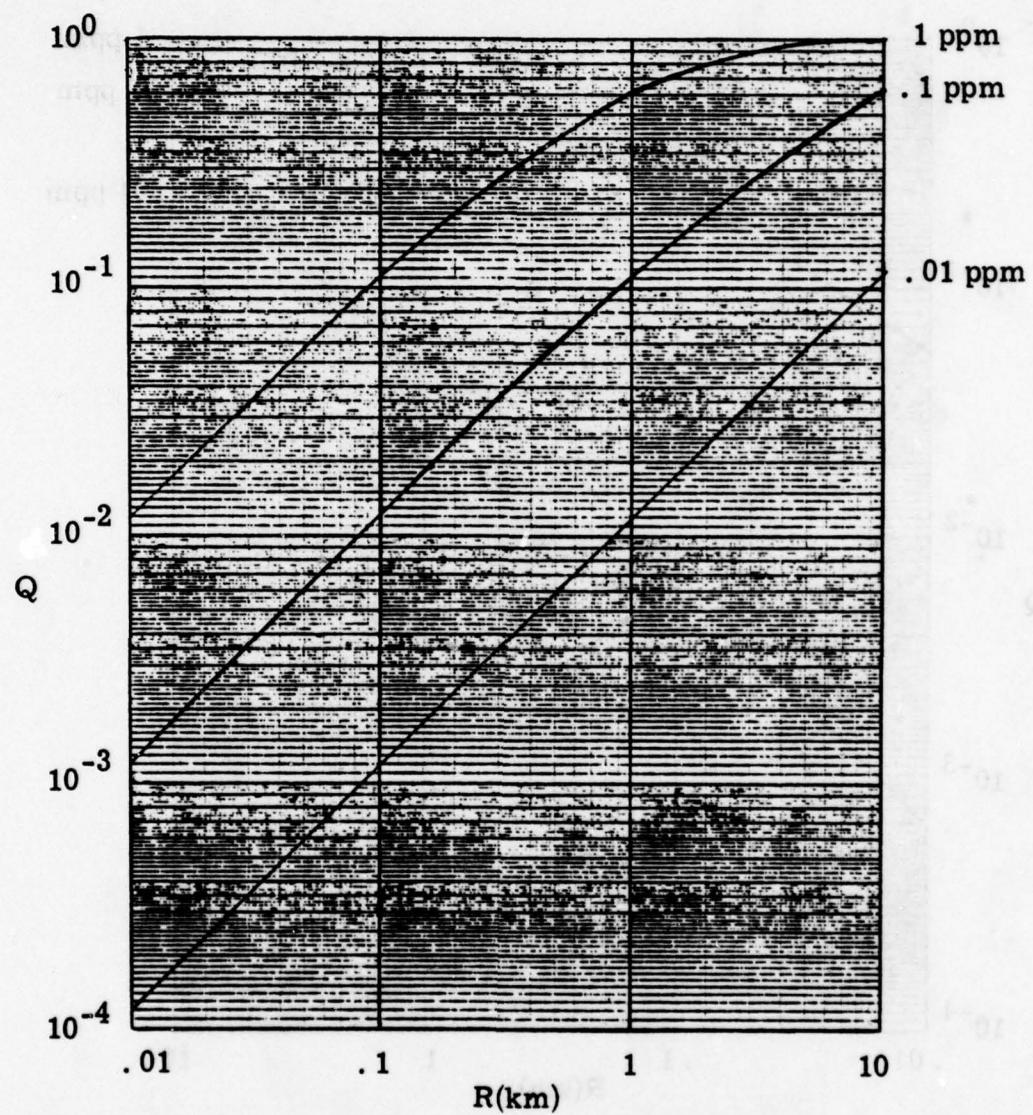


Figure 7. 3. 6-8g.  $Q$  for PAN versus range for three levels of concentration.

7. 3. 6. 4q

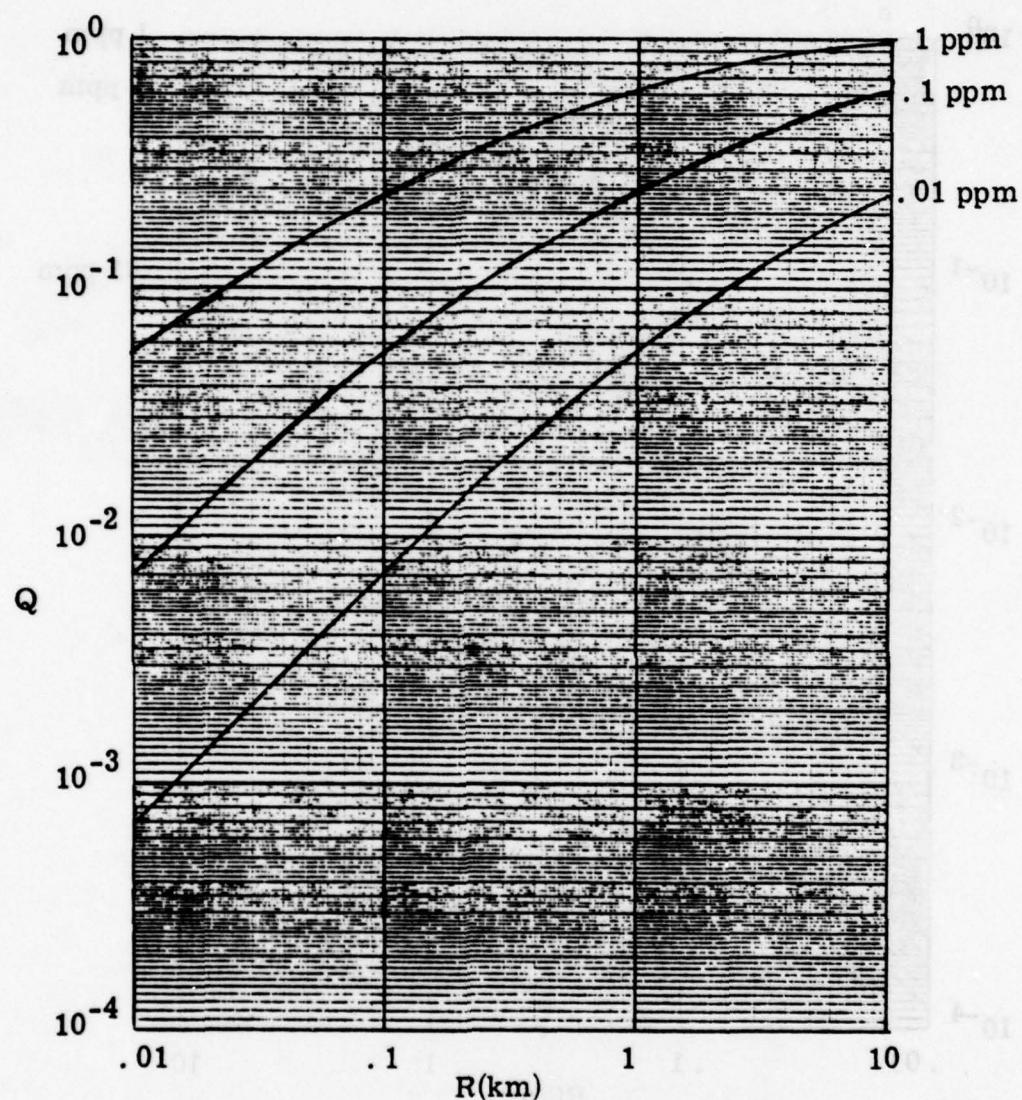


Figure 7. 3. 6-8h.  $Q$  for  $\text{C}_2\text{H}_4$  versus range for three levels of concentration.

7.3.6.4r

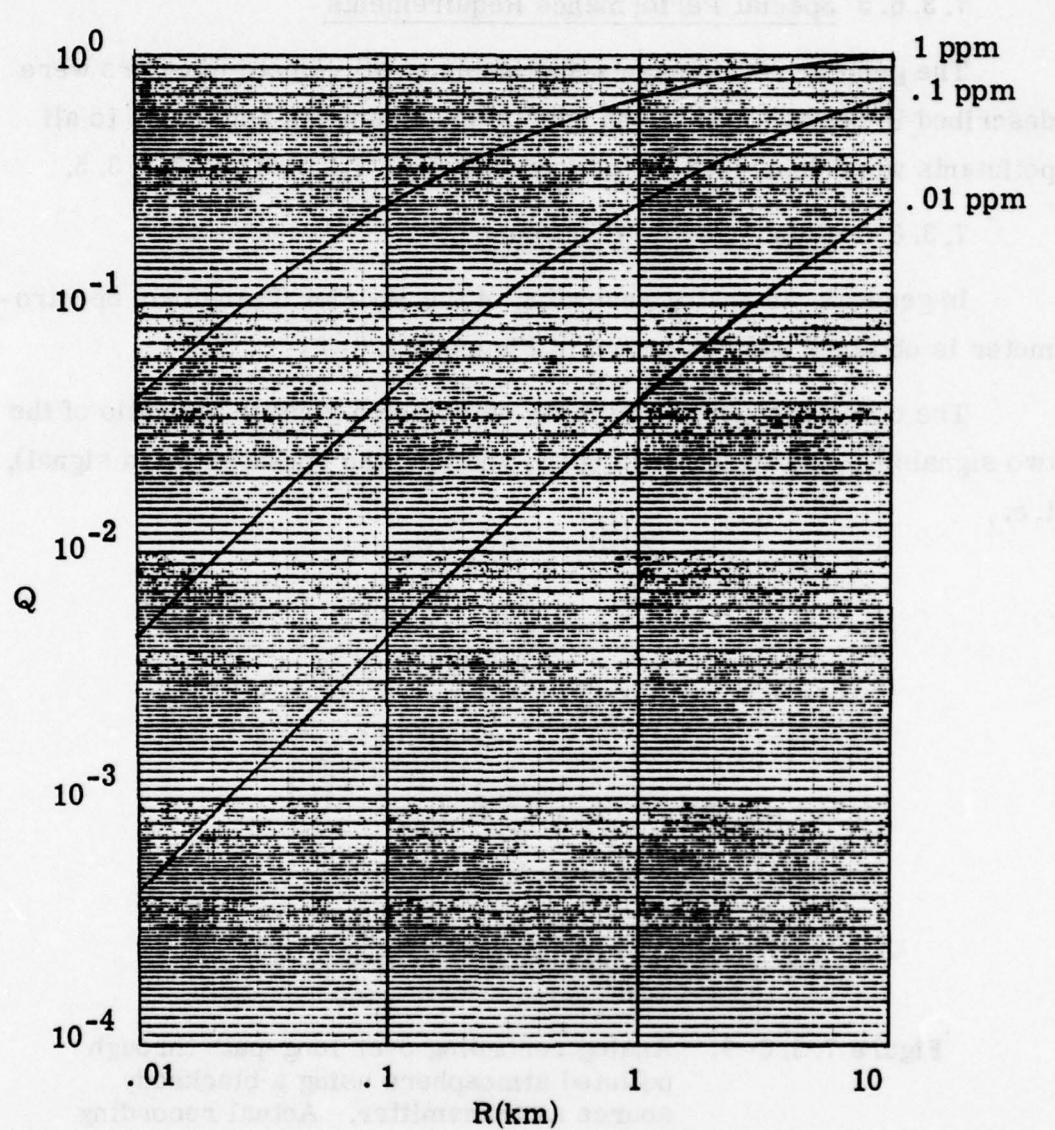


Figure 7.3.6-8i.  $Q$  for  $\text{C}_6\text{H}_6$  versus range for three levels of concentration.

### 7.3.6.5 Special Performance Requirements

The general requirements applicable to all remote monitors were described in Section 7.1.1, and special requirements applicable to all pollutants were described in Sections 7.2.1.5, 7.2.2.5 and 7.2.3.5.

### 7.3.6.6 Data Analysis Procedure

In general, an analog recording of the Fourier Transform Spectrometer is obtained such as shown in Figure 7.3.6-9.

The concentration is implicitly determined through the ratio of the two signals  $S_1$  (the attenuated signal) and  $S_1^0$  (the non-attenuated signal), i.e.,

$$(W/d)_1 = \ln S_1^0 / S_1$$

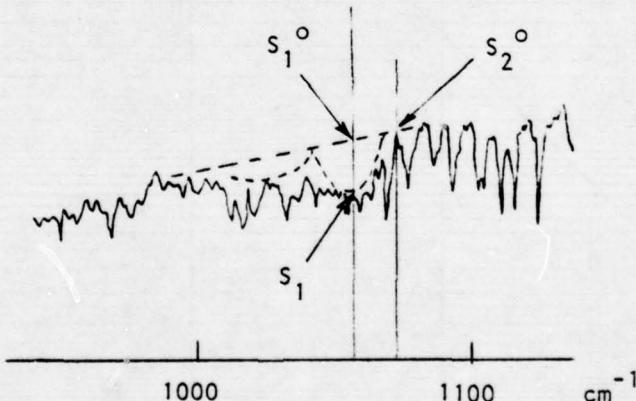


Figure 7.3.6-9. Analog recording over long-path through polluted atmosphere using a blackbody source as transmitter. Actual recording of field data.

where

$$W/d = kCR(1 + kCR/4a)^{-1/2}.$$

Since  $S_1^0$  cannot be measured directly, it must be related to a spectral region where there is a known amount of absorption due to the natural species ( $\text{H}_2\text{O}$ ,  $\text{CO}_2$ , etc.). This relationship is given by

$(P_{\text{eff}})_{\text{min}}$

7. 3. 6. 6b

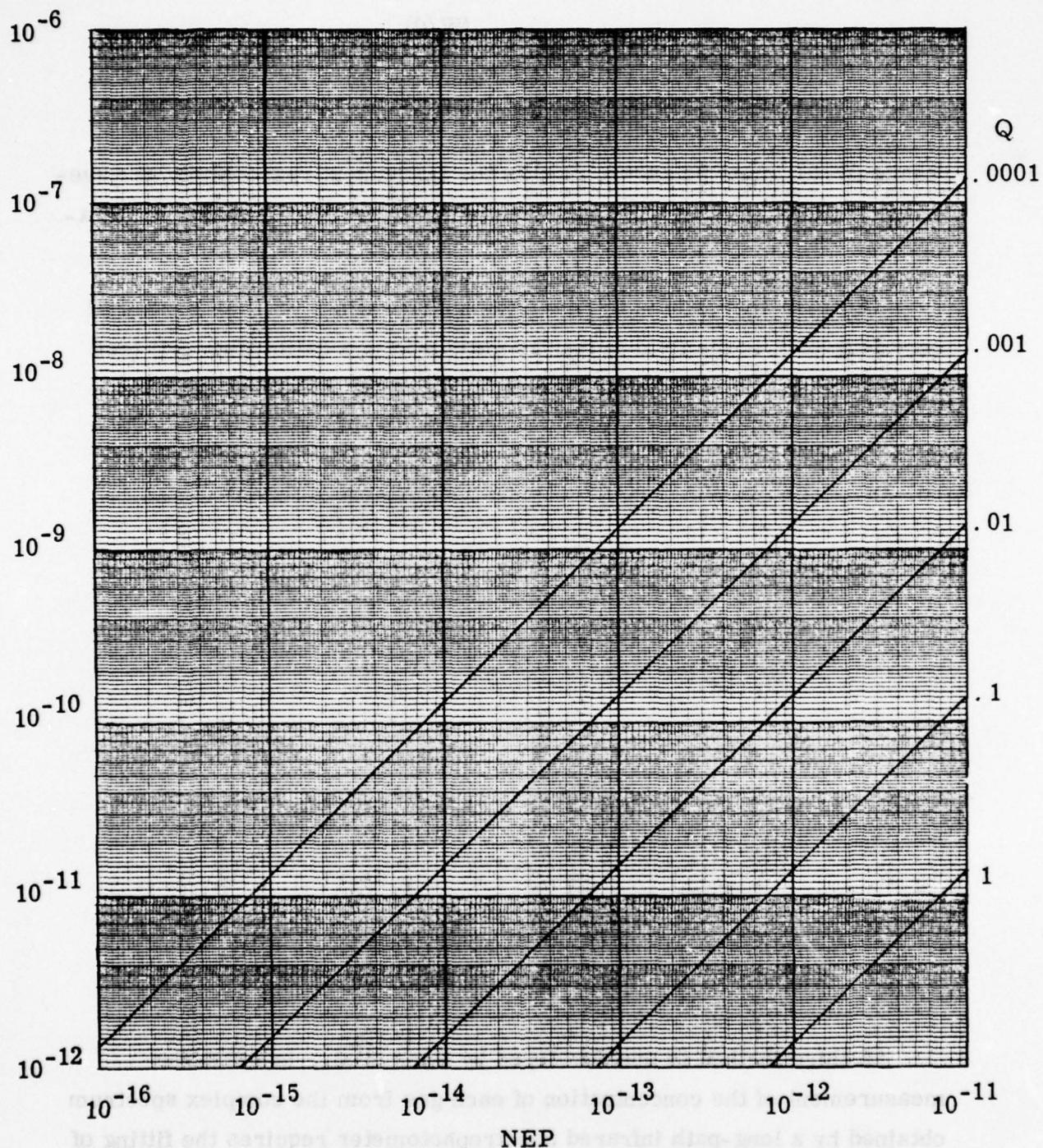


Figure 7. 3. 6-10.  $(P_{\text{eff}})_{\text{min}}$  versus NEP for different values of  $Q$ .

$$S_1^0 = \frac{N^0(\lambda_1, T)}{N^0(\lambda_2, T)} \frac{R(\lambda_1)}{R(\lambda_2)} e^{(W/d)_2 S_2^0}$$

where  $(W/d)_2$  must be known,  $R(\lambda)$  is the instrument responsivity at wavelength  $\lambda$  and  $N^0(\lambda, T)$  is the source radiation at wavelength  $\lambda$  and temperature  $T$ .

Another approach is to relate the signal ratio  $S_1/S_1^0$  as measured over long-path in the field to that as measured in a calibration cell (see Figure 7.3.6-11). Of course, the value  $S_1^0$  must still be established reliably in the field data.

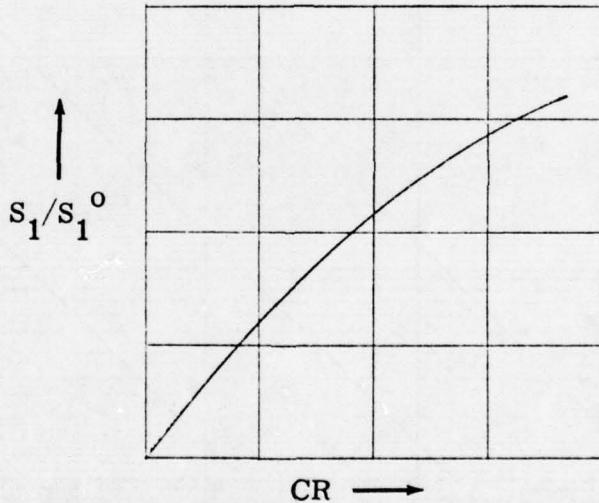


Figure 7.3.6-11. Conceptual calibration curve  $S_1/S_1^0$  versus the product concentration  $\bar{x}$  range.

A third method is one developed by Derr et al., in which the measurement of the concentration of each gas from the complex spectrum obtained by a long-path infrared spectrophotometer requires the fitting of trial spectra composed from a library of spectra. The fitting procedure adjusts the concentrations of the trial spectra until a "best-fit" in a least squares sense is produced. A detailed description of this procedure can be found in Reference 169.

7.3.7 IR Long-Path with Broadband Source Using Gas Filter Correlation Receiver

7.3.7.1 Principle of Operation

Gas filter correlation is a method of determining the concentration of pollutant gas species by measuring the correlation between the unknown atmospheric spectrum and the spectrum of a known sample of the specific pollutant gas which is contained in the instrument. The spectra of other gases have near zero correlation with the spectrum of this particular species and so are intrinsically discriminated against.

The radiant source is broadband and the receiver is non-dispersive. The radiant energy received from the source is passed alternately through the sample of the particular species and through a neutral absorber having the same total transmission as the gas sample. Radiation is absorbed in the gas cell only at those specific spectral line wavelengths which are characteristic of that gas species; in the neutral absorber radiation is absorbed equally at all wavelengths.

The difference in the source energy removed by the gas and the neutral absorber is the desired pollutant concentration signal. If the correlation coefficient between the spectra of the standard and the unknown is zero (random spectral line overlap) the same total energy will be removed from the beam by the neutral and the gaseous absorbers and no net signal results. If the correlation coefficient between the spectra is plus unity (exact spectral line overlap) a signal will result: Less change will be observed in the source energy when transmitted through the gas cell, as compared to the neutral absorber, because the exact wavelengths at which energy is selectively attenuated by the gas cell have already been attenuated by the pollutant, but the neutral absorber will attenuate the source energy non-selectively. The result is a difference signal proportional only to the specific pollutant's absorption. This signal is related by calibration to the average concentration of the specific pollutant over the path between the source and receiver.

### 7. 3. 7. 2 System Description

The system consists of a broadband radiant source covering the wavelength interval of the pollutant spectral band and a receiver to examine the source radiation after its absorption by the intervening atmosphere.

The system may be bistatic, with a separated source and receiver, or monostatic wherein the source and receiver are adjacent and with a retroreflector defining the far end of the monitored region. In this latter case, the sensitivity is increased because the beam traverses the monitored region twice.

The source is generally a blackbody and is chopped so that its radiation can be distinguished at the detector from spurious background radiation.

The mechanism for alternating the beam between the gas cell and the neutral absorber may be either at the source or at the detector.

A diagram of a typical instrument is shown in Figure 7. 3. 7-1.

### 7. 3. 7. 3 System Parameters

#### Source

Numerous commercial radiant sources are available which approximate the blackbody function over the infrared wavelength interval of interest. Temperatures available range to 1800K; 1100K is typical. Higher temperatures may not provide the expected signal improvement as they may necessitate a decrease in the instrument A  $\Omega$  parameter. A  $\Omega$  is the product of the aperture area A and the solid angle (field of view)  $\Omega$ . It determines the power collected from a field of radiance and

### 7. 3. 7. 3b

is therefore a general indicator of sensitivity. A  $\Omega$  is sometimes called "light grasp" or "etendue".

Throughout a given optical system the beam cross-section area and the beam convergence angle may change individually, but geometric optical laws dictate that their product remains constant. For this reason the A  $\Omega$  parameter is also given the names "throughput" and "optical invariant".

Spectral radiance for blackbody sources is given in Figure 7. 3. 7-3 as a function of temperature and wavelength.

Systems using a natural source (hillside, etc.) are not included in this section. They are described in Section 7.3.10, Passive Downward Looking Systems.

#### Operational Wavelengths

The operational wavelength and wavelength interval used depends on the specific pollutant gas to be detected. Typical wavelengths are:

CO	4. 5 - 4. 8 $\mu\text{m}$
Hydrocarbons	3. 0 - 4. 0 $\mu\text{m}$
	9. 5 - 12. 0 $\mu\text{m}$
NO	5. 1 - 5. 5 $\mu\text{m}$
NO <sub>2</sub>	3. 3 - 3. 6 $\mu\text{m}$
SO <sub>2</sub>	3. 95 - 4. 05 $\mu\text{m}$
	8. 4 - 9. 0 $\mu\text{m}$

Wavelengths must be selected on the basis of spectral band parameters and freedom from interfering species, especially water vapor.

7.3.7.3c

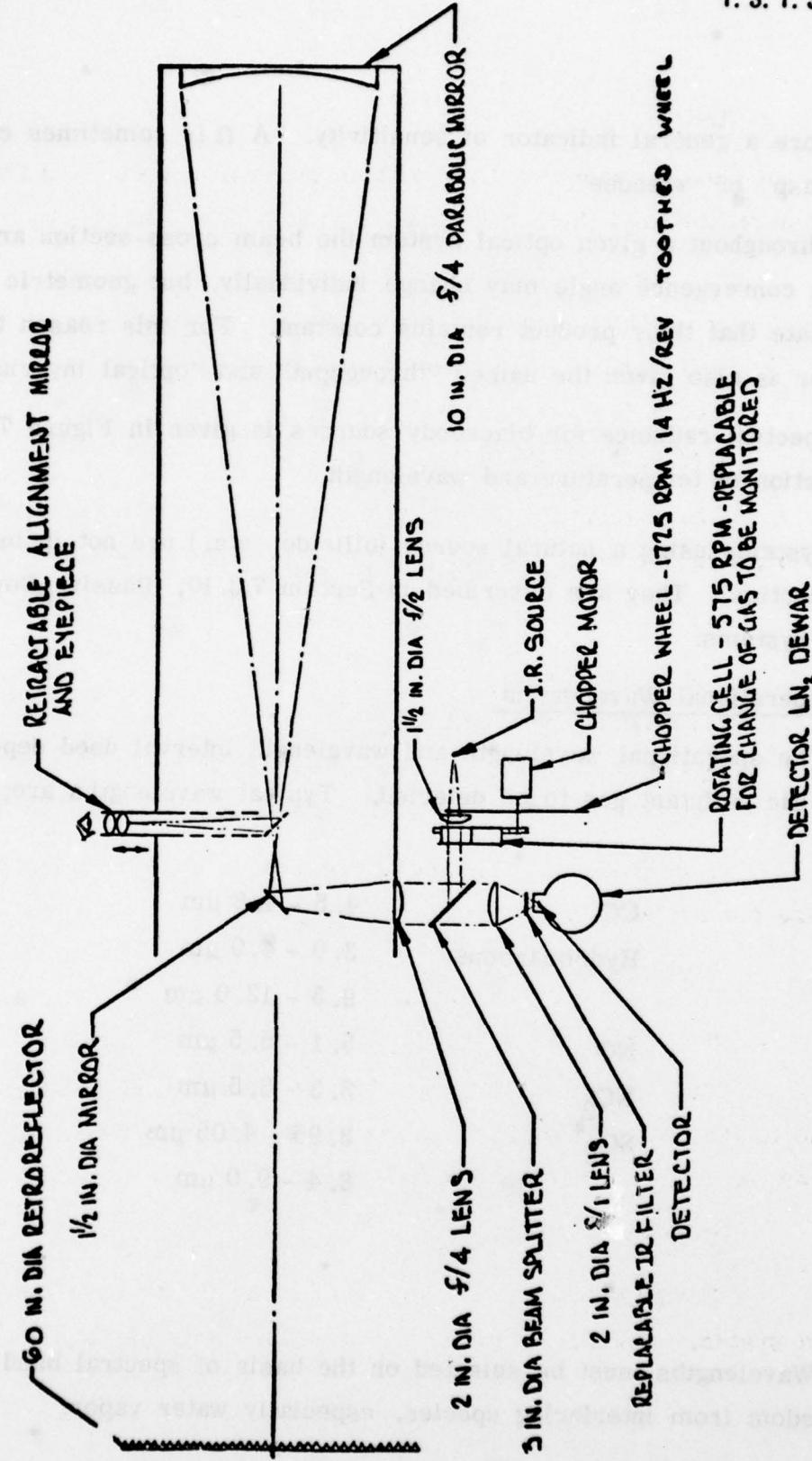


FIGURE 7.3.7-1. Optical Layout Long-Path Gas Analyzer  
Filter Correlation Receiver

Detectors

Some commercially available detectors, their operating temperature, and their regions of optimum performance are:

PbS	(193K)	2 - 3 $\mu$ m
PbSe	(193K)	2 - 5 $\mu$ m
InSb	( 77K)	2 - 5 $\mu$ m
Pb(Sn, Te)	( 77K)	5 - 10 $\mu$ m
Hg(Cd, Te)	( 77K)	7 -12 $\mu$ m

Characteristics values of the parameters  $D^*$  for these detectors are shown in Figure 7. 3. 7-2.

Optics

Entrance aperture,	$A_o$
Entrance solid angle,	$\Omega_o$
Optical efficiency,	$\eta_o$ (net transmission)
Detector optics,	$A_d \Omega_d = A_o \Omega_o$ for optimum design

These optical parameters are chosen by the designer to optimize the system performance.

Electronics

Electronic efficiency,  $\eta_e$

The electronic efficiency is the reduction in signal-to-noise due to the data processing. It may be appreciably less than unity even for a detector-noise-limited system.

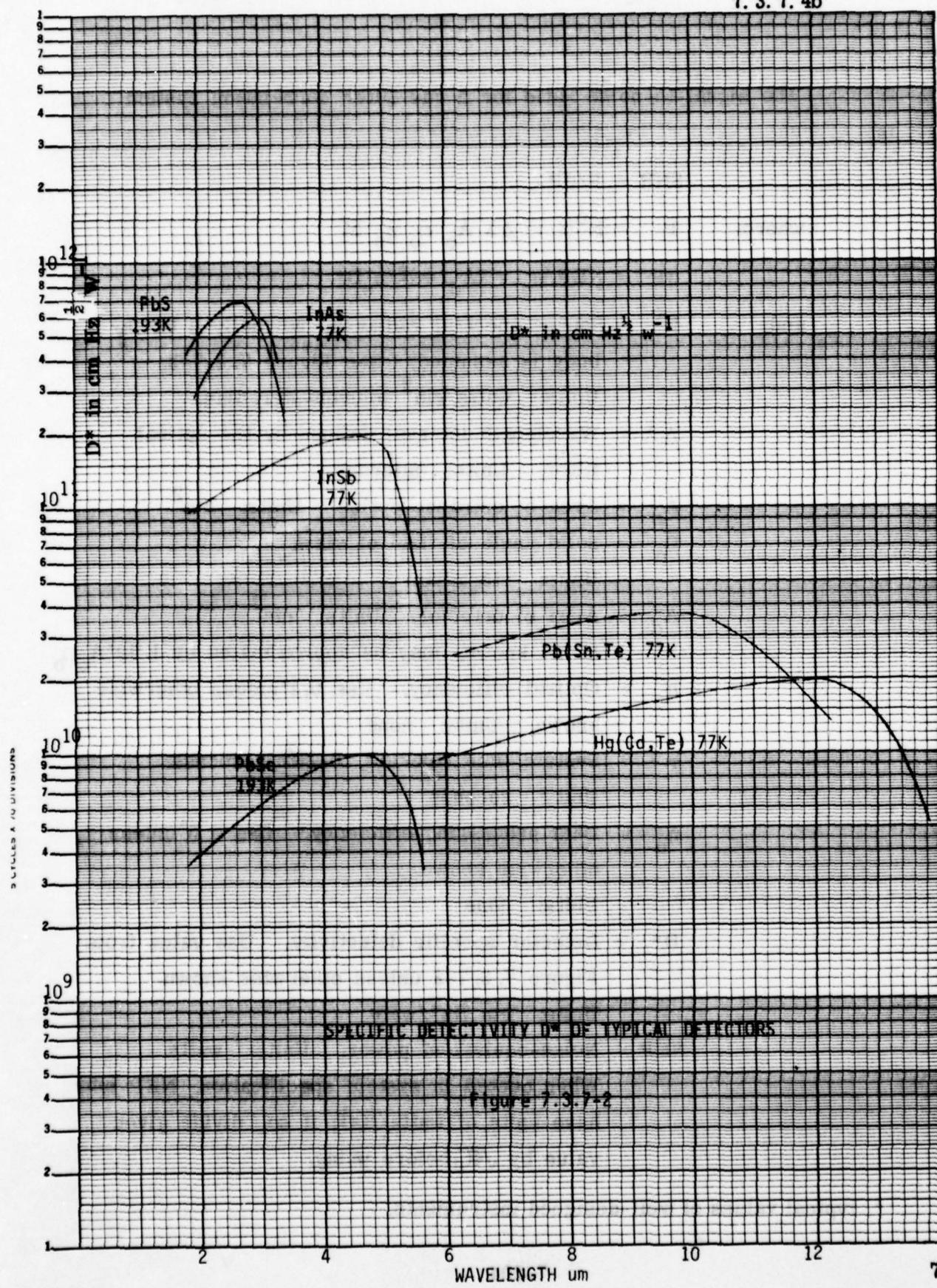
Electronic Bandpass,  $\Delta_f$ 

Generally  $\Delta_f = 1/4 t_c$  where  $t_c$  is the 0-63% time constant of the system readout, however, this can vary with electronics design.

#### 7. 3. 7. 4 Theoretical Performance Prediction

Based upon known or assumed system parameters, an approximate performance prediction can be made. The accuracy of these calculated results will be dependent on the accuracies of the parameter values used and on the degree to which the system design conforms to the assumed theoretical model.

### 7. 3. 7. 4b



The signal-to-noise ratio for a gas filter correlation system is:

$$\text{SNR} = P/dP$$

where:  $P = N^0(\lambda, \tau) \Delta \lambda A_o \Omega_o \eta_o M$

$$dP = \text{NEP}/\eta_e = (A_d/4\tau)^{\frac{1}{2}}/\eta_e D^*$$

and:  $N^0$  = Source spectral radiance, normally a black-body is assumed. See Figure 7.3.7-3.  
Units: watts/cm<sup>2</sup> micron-steradian.

$\Delta \lambda$  = Wavelength interval defined by the optical filter. Units: microns

$A_o$  = Area of entrance optics. Units: cm<sup>2</sup>

$\Omega_o$  = Solid angle of field of view.  
Units: steradians

$A_d$  = Area of detector. Units: cm<sup>2</sup>

If not known, may be approximated by  $1.59^* A_o \Omega_o$

$\eta_o$  = Optical efficiency. Use 0.1\*unless otherwise known. Units: none

$\tau$  = System time constant, 0-63% response.  
Units: seconds

$\eta_e$  = Data processing efficiency. Use 0.3\*unless otherwise known.

Units: none

$D^*$  = Detector specific detectivity. Use value from Figure 7.3.7-2 unless otherwise known.  
Units: cm Hz<sup>1/2</sup>/watt

NEP = Noise-equivalent power. Units: watts.  
When quoted in system specification, NEP may have units of watts/Hz<sup>1/2</sup>; if so, divide given value by  $\sqrt{4\tau}$  before using.

\* typical values of well-designed instruments.

### 7. 3. 7. 4d

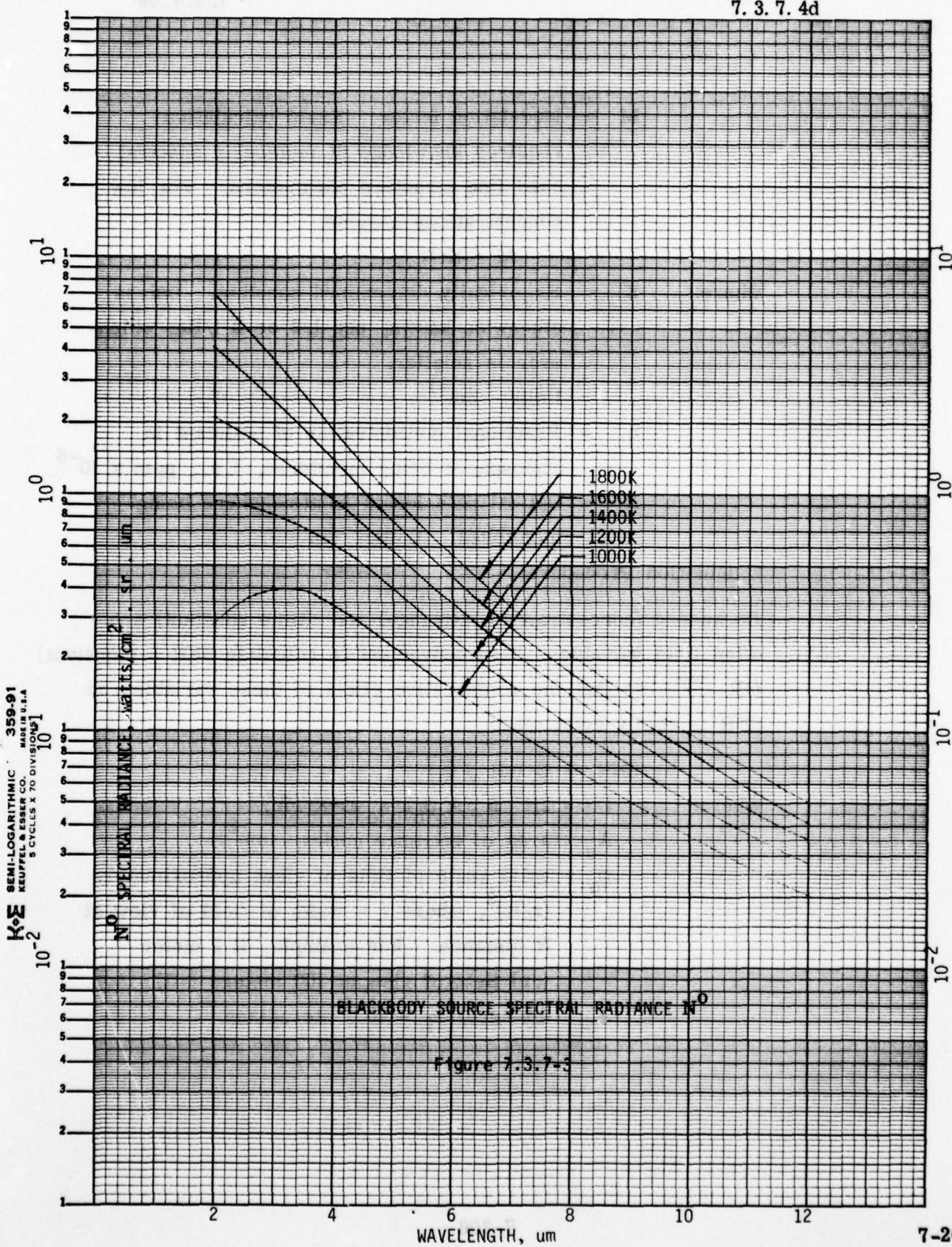


Figure 7.3.7-3

**M** = Modulation factor. Exact calculation requires knowledge of molecular spectral band fine structure parameters. For low concentrations assume:

$$M \approx KcR$$

where: **K** = Empirically determined constant. Unless otherwise known, use 1.0 or  $0.1/R_c$ : whichever is smaller.

Units:  $\text{cm}^{-1}$

**c** = Fractional concentration of pollutant in atmosphere being monitored, i.e.,  $\text{ppm} \times 10^{-6}$

**R** = Optical path length in atmosphere being monitored. Units: cm

#### Calculation Procedure:

Because **c** (concentration), **R**(range) and  $\tau$ (time constant) are often field variables, it is convenient to calculate  $\text{SNR} = (\text{constant})(cR\sqrt{\tau})$  so that the comparative effect of these variables on SNR is easily determined.

$$\text{SNR} = G(cR\sqrt{\tau})$$

Where: **G** =  $2N^0 \Delta \lambda A_o \Omega_o \eta_o \eta_e D^* K / \sqrt{A_d}$

**A<sub>o</sub>** = area of entrance optics, ( $\text{cm}^2$ )

**$\Omega_o$**  = solid angle of field of view; approximately  $(r/R)^2$ , where **r** = width of field of view at **R** distance. For example, if 1 meter (=r) field of view at 100 meters (=R) distance,  $\Omega_o = 10^{-4}$  steradians.

### Analytical Determination of SNR

The above equation can be used to calculate a predicted value of SNR. Unless otherwise known the following values can be assumed for the variables defined above:

$A_o$  = area of entrance optics, ( $\text{cm}^2$ )

$\Omega_o$  = solid angle of field of view; approximately  $(r/R)^2$ , where  $r$  = width of field of view at

$R$  distance. For example, if 1 meter (=r) field of view at 100 meters (=R) distance,  $\Omega_o = 10^{-4}$  steradians.

$N^0$ : assume Figure 7.3.7-4

$\Delta\lambda$ : assume  $0.1 \mu\text{m}$

$A_d$ : assume  $1.59 A_o \Omega_o$

$\eta_o$ : assume 0.1

$\eta_e$ : assume 0.3

$D^*$ : assume Figure 7.3.7-2

$k$ : assume 1.0 or  $0.1/R_c$ , whichever is smaller

$\tau$ : instrument time constant, seconds

$c$ : concentration,  $\text{ppm} \times 10^{-6}$

$R$ : range, cm

Step 1: Calculate  $G = 2N^0 \Delta \lambda A_o \Omega_o \eta_o \eta_e D^* k / \sqrt{Ad}$

Use known experimental values or approximate values given above.

This value of G can now be used for various values of c, R, and  $t_c$  which are often field variables.

Step 2: To calculate SNR given c, R,  $t_c$ :

$$\text{SNR} = G c R / \sqrt{t_c}$$

Step 3: To calculate c given SNR, R,  $t_c$ :

$$c(\text{ppm} \times 10^{-6}) = \text{SNR}/G R \sqrt{t_c}$$

### Graphical Determination of SNR

#### Graphical Determination of SNR

We assume the following typical values in the calculation of G, above. Known values are always preferred over these typical values.

$$A_o = 300 \text{ cm}^2$$

$$\Omega_o = 2 \times 10^{-5} \text{ sr}$$

$$N^0 = 0.3 \text{ watt cm}^{-2} \text{ sr}^{-1} \mu\text{m}^{-1} \text{ for wavelengths 3 to } 6 \mu\text{m}$$

$$0.05 \text{ watt cm}^{-2} \text{ sr}^{-1} \mu\text{m}^{-1} \text{ for wavelengths 6 to } 12 \mu\text{m}$$

$$\Delta\lambda = 0.1 \mu\text{m}$$

$$A_d = 1.59 A_o \Omega_o \text{ cm}^2$$

$$\eta_o = 0.1$$

$$\eta_e = 0.3$$

$$D^* = 10^{11} \text{ cm Hz}^{\frac{1}{2}} \text{ w}^{-1} \text{ for wavelengths 3 to } 6 \mu\text{m}$$

$$2 \times 10^{10} \text{ cm Hz}^{\frac{1}{2}} \text{ w}^{-1} \text{ for wavelengths 6 to } 12 \mu\text{m}$$

$$k = 1.0$$

We leave the quantities c, R, and  $\tau$  as variables.

**Step 1:** Calculate:  $cR$

Assume:  $R$ , range in meters. Double distance if monostatic system with retroreflector is used.  $c$ , pollutant concentration in ppm

Result: Figure 7. 3. 7-4 gives values of the product  $cR$  in units of cm atm.

**Step 2:** Calculate:  $cR\sqrt{t_c}$

Assume:  $t_c$ , time constant, seconds

Result: Figure 7. 3. 7-5 gives values of the product  $cR\sqrt{t_c}$ .

**Step 3:** Calculate: SNR, signal-to-noise ratio

Assume:  $cR\sqrt{t_c}$  from Step 2.

Result: Figure 7. 3. 7-6 gives SNR for the two cases:

a. 3 to 6  $\mu\text{m}$  wavelength

b. 6 to 12  $\mu\text{m}$  wavelength

for the typical instrument parameters assumed.

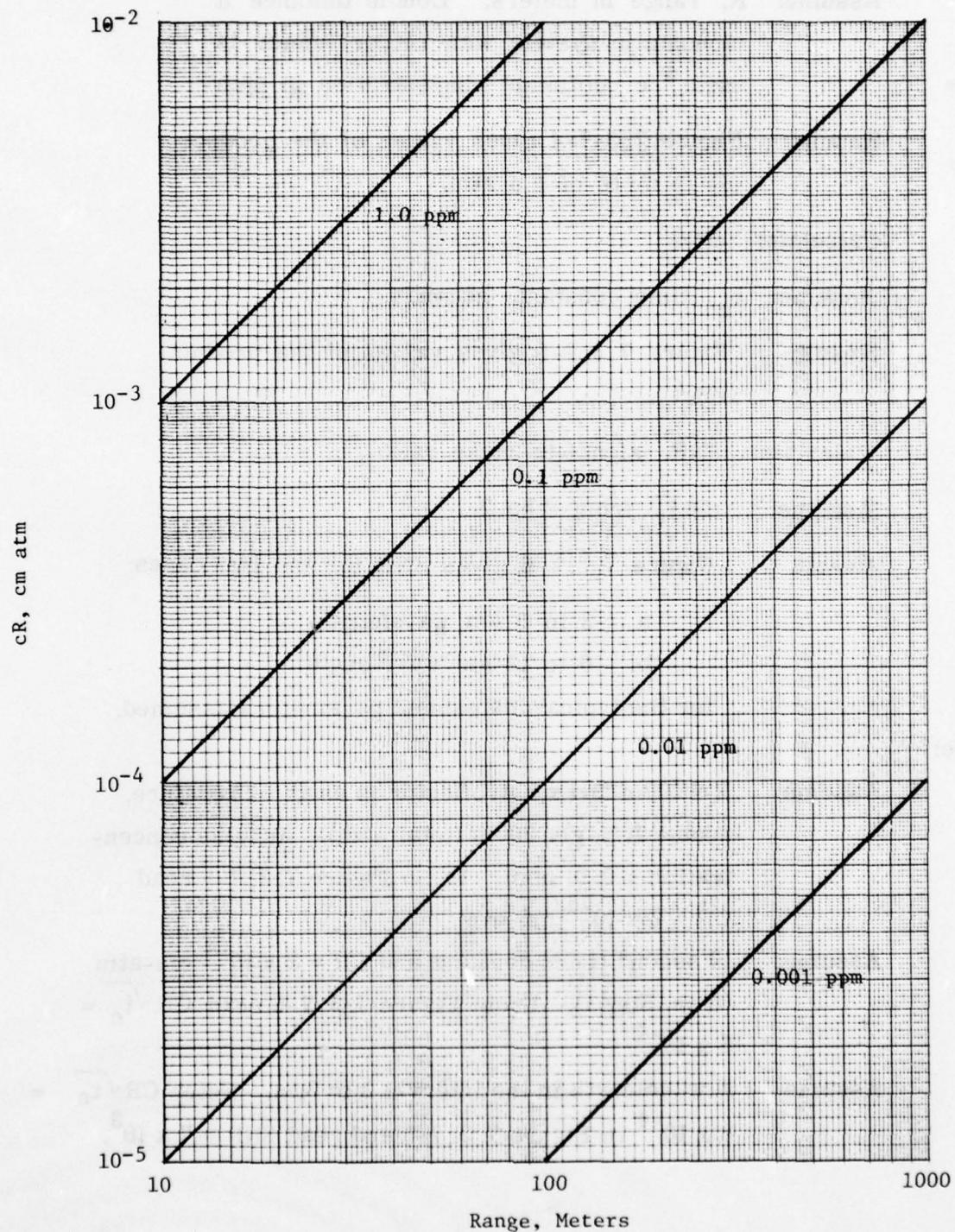
**Example:**

**Step 1:** Assume:  $R = 100\text{m}$  and a retroreflector is used. Therefore, double  $R$  to get  $200\text{m}$  (total path). Assume concentration = 0.01 ppm. From Figure 7. 3. 7-4 read  $CR = 2 \times 10^{-4} \text{ cm-atm}$ .

**Step 2:** Assume: 10 second time constant and  $CR = 2 \times 10^{-4} \text{ cm-atm}$  (from Step 1). From Figure 7. 3. 7-5 read  $CR\sqrt{t_c} = 6 \times 10^{-4}$ .

**Step 3:** Assume: A wavelength in the interval 3 to 6  $\mu\text{m}$ . Enter  $CR\sqrt{t_c} = 6 \times 10^{-4}$  in Figure 7. 3. 7-6 and read  $\text{SNR} = 7 \times 10^3$ .

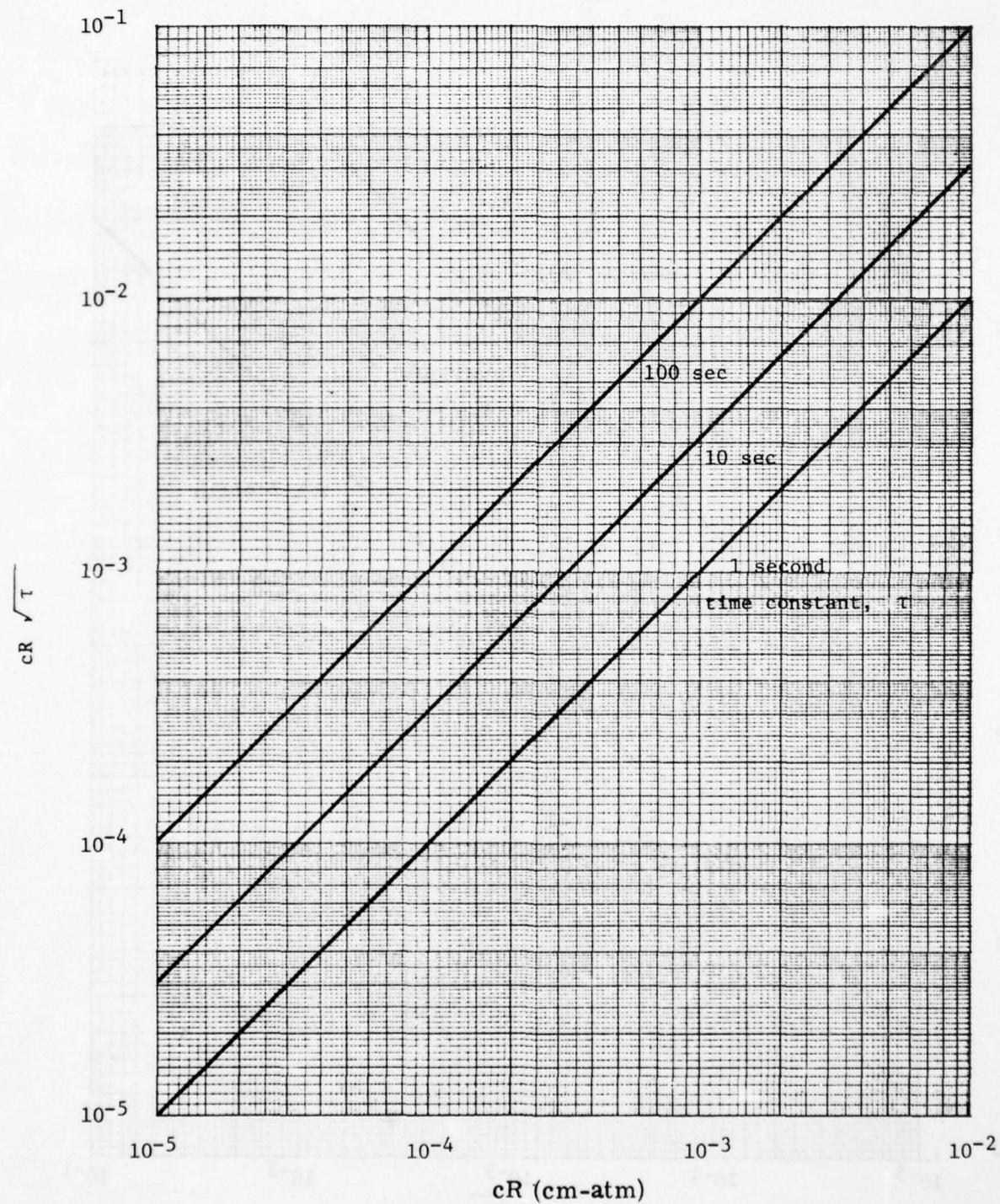
7. 3. 7. 4i



Graphical Analysis of SNR, Step 1

Fig. 7.3.7-4

7.3.7.4j



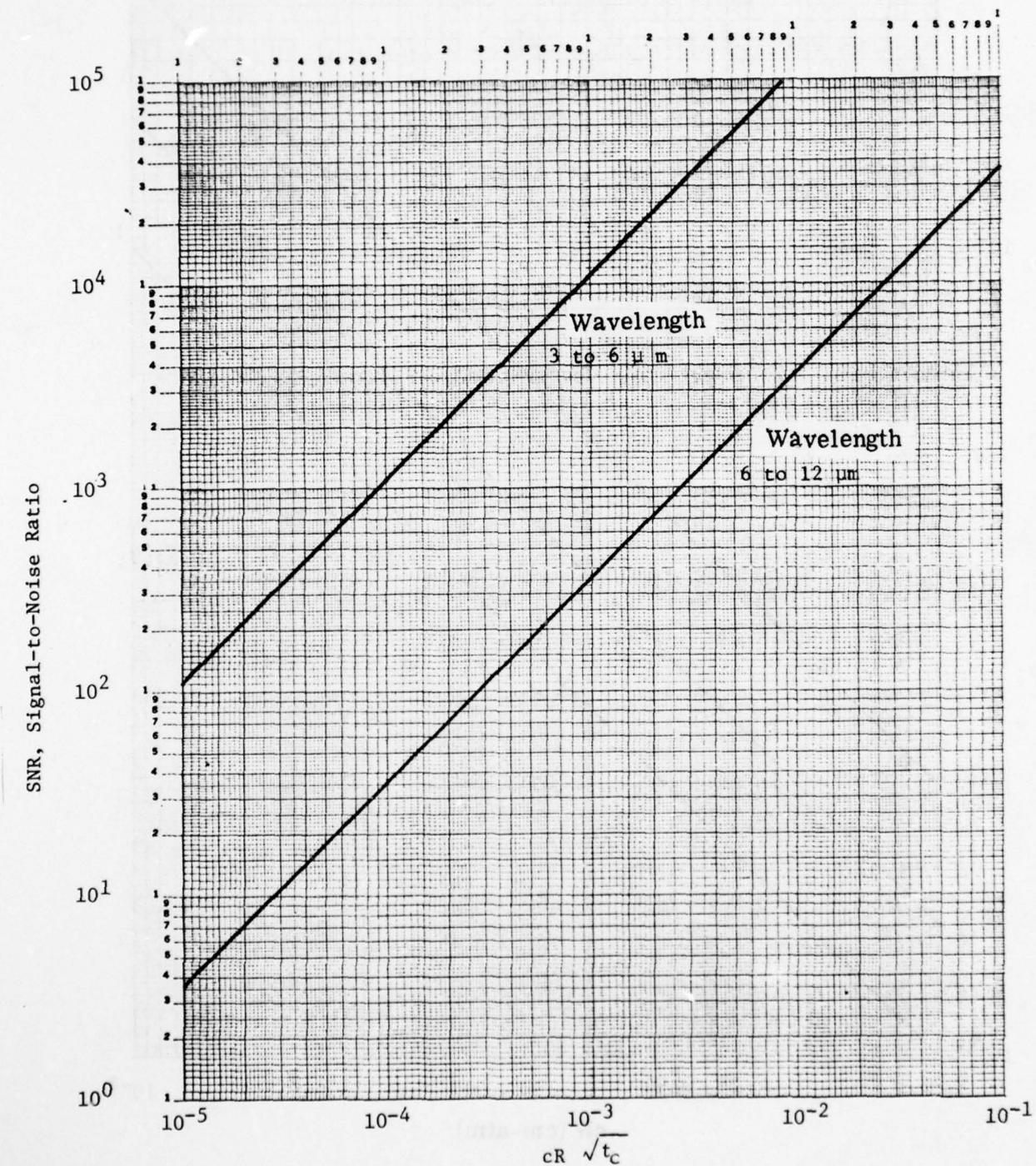
Graphical Analysis of SNR, Step 2

Fig. 7.3.7-5

7. 3. 7. 4k

K-E LOGARITHMIC 3 X 5 CYCLES  
KEUFFEL & ESSER CO. MADE IN U.S.A.

46 7522



Graphical Analysis of SNR, Step 3

Fig. 7.3.7-6

#### 7. 3. 7.5 Special Performance Requirements

The non-special requirements were discussed in Section 7.1, Procedures Applicable to All Remote Sensors.

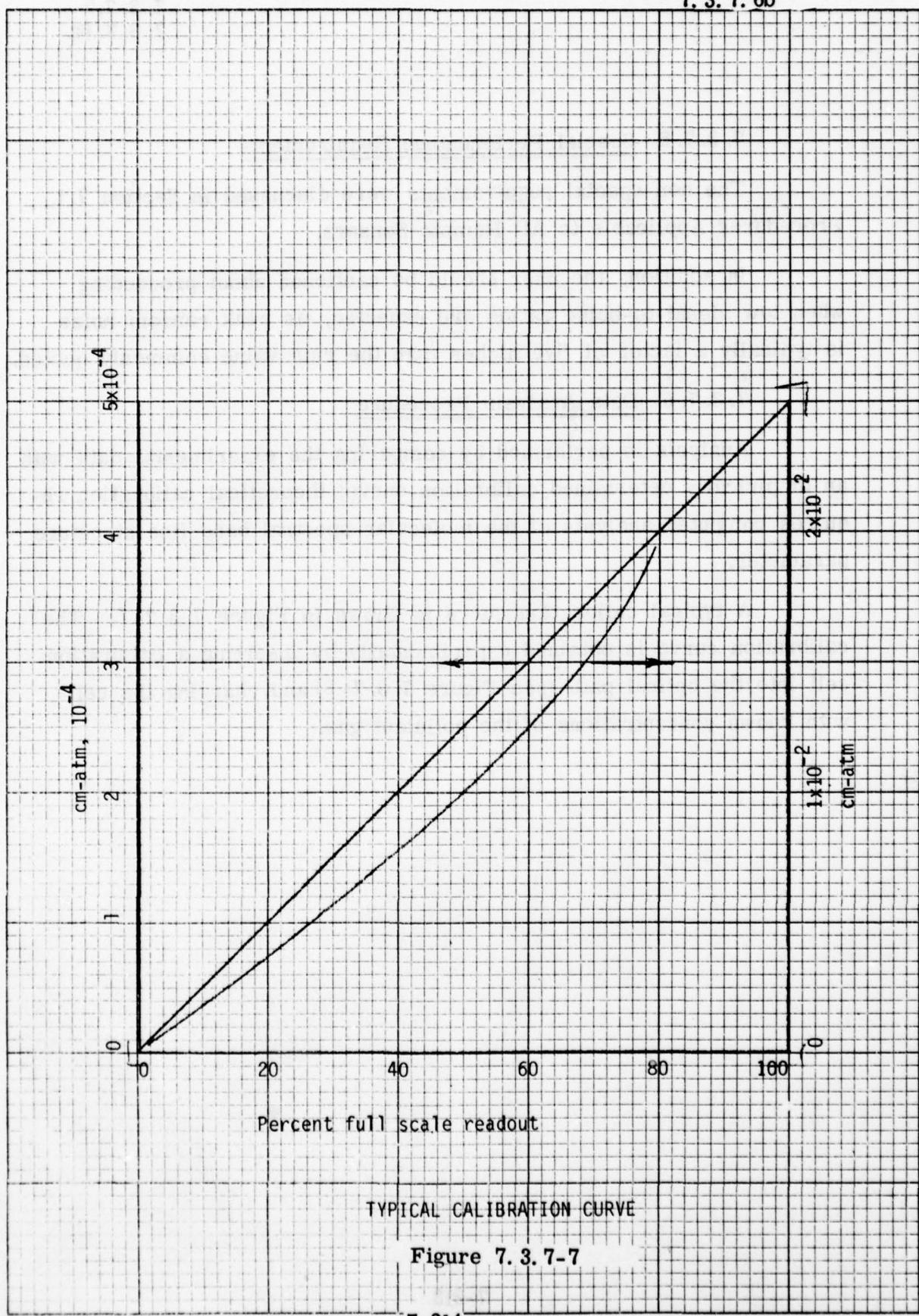
In addition, the user should be cautioned about proceeding when low signal-to-noise ratios are expected, as peak random noise is typically a factor of five higher than the rms value commonly quoted.

#### 7. 3. 7.6 Data Analysis Procedure

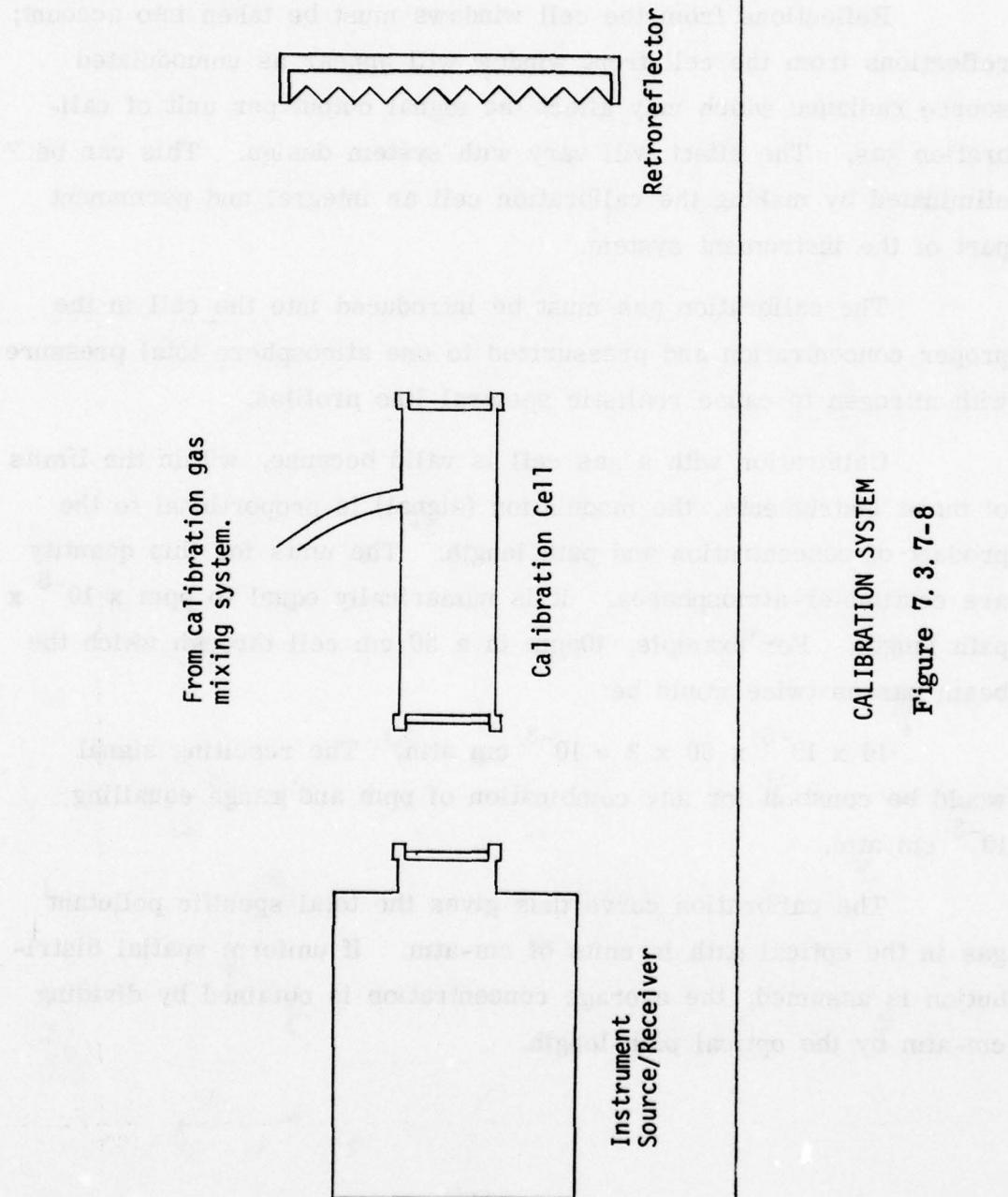
Analysis is performed by comparing the experimental data with an empirically determined calibration curve; theoretical calibration requires computer analysis of the molecular spectral band fine structure parameter.

A typical calibration curve is shown in Figure 7.3.7-7. The calibration curve is obtained experimentally by inserting a calibration cell into the optical path (see Figure 7.3.7-8) and charging the cell with known concentrations of the pollutant gas.

7. 3. 7. 6b



**7. 3. 7. 6c**



**CALIBRATION SYSTEM**

**Figure 7. 3. 7-8**

Precautions must be taken when using a calibration cell.

Reflections from the cell windows must be taken into account; reflections from the cell front window will appear as unmodulated source radiance which may affect the signal output per unit of calibration gas. The effect will vary with system design. This can be eliminated by making the calibration cell an integral and permanent part of the instrument system.

The calibration gas must be introduced into the cell in the proper concentration and pressurized to one atmosphere total pressure with nitrogen to cause realistic spectral line profiles.

Calibration with a gas cell is valid because, within the limits of these instruments, the modulation (signal) is proportional to the product of concentration and path length. The units for this quantity are centimeter-atmospheres. It is numerically equal to ppm  $\times 10^{-6}$   $\times$  path length. For example, 10ppm in a 50 cm cell through which the beam passes twice would be:

$$10 \times 10^{-6} \times 50 \times 2 = 10^{-3} \text{ cm atm.}$$

The resulting signal would be constant for any combination of ppm and range equalling  $10^{-3}$  cm atm.

The calibration curve thus gives the total specific pollutant gas in the optical path in units of cm-atm. If uniform spatial distribution is assumed, the average concentration is obtained by dividing cm-atm by the optical path length.

7. 3. 8 IR Long-Path with Broadband Source Using Filterwheel Receiver

7. 3. 8. 1 Principle of Operation

A filterwheel receiver utilizing a broadband radiant source operates as a narrowband radiometer to measure the total absorption in an interval of the spectral band of the specific pollutant. The pollutant concentration is determined using this data plus knowledge of the path length and the instrument calibration curves.

In principle, data must be taken through two filters - one in the pollutant absorption band and one outside the band - to yield the ratio  $I/I_0$  from which the concentration can be deduced. In practice, more than two filters are employed in order to remove the effects of superimposed absorption of other gas species.

This latter point, the lack of inherent specificity, is the cause of the performance limitation of filterwheel radiometer instruments. The current state of performance of narrowband optical filters limits the passband to not less than about one percent of the center wavelength, or about  $0.05 \mu\text{m}$  at  $5 \mu\text{m}$ . No infrared pollutant absorption band is completely free from overlap of atmospheric lines and/or other pollutant lines, and considerable spectral interference exists between individual species that are normally present in polluted atmospheres at the spectral resolution of high quality radiometers. Water vapor is a particularly prevalent source of interference. Many filters at carefully chosen wavelengths are often incorporated to provide a set of data which in conjunction with knowledge of the spectral parameters of interfering species is used to correct for the spurious absorption.

If it is known that the circumstances do not require a high specificity instrument, a filterwheel radiometer has the positive qualities of high sensitivity, fast response, and low complexity.

#### 7. 3. 8. 2 System Description

The system consists of a broadband radiant source covering a wavelength interval greater than the extent of the absorption band of the pollutant, and a receiver to examine the source radiation after its absorption by the intervening atmosphere. The system is bistatic; the source and receiver may be separated or they may be adjacent and a retroreflector used to define the far end of the monitored region.

The source is generally a blackbody and is chopped so that its radiation can be distinguished at the detector from spurious background radiation.

The receiver consists of a telescope or other foreoptics to collect the radiation, a filterwheel to sequentially position two or more narrow band filters into the beam, secondary optics to focus the beam onto the detector, plus the necessary electronics for control and data processing.

Figure 7. 3. 8-1 is a diagram of a filterwheel radiometer built by Bendix for EPA for measuring pollutant spectra in the  $7-14 \mu\text{m}$  region (Ref. 180). Instead of a set of discrete wavelength filters, in this instrument the wavelength is scanned by rotating a continuously variable filter wheel which has a resolution of about one percent. The radiation is collected by a 28 cm aperture telescope and passed through the filter wheel to a mercury-doped germanium detector cooled by mechanical refrigeration to 28K. An on-line computer is used to analyze

7.3.8.2b

the spectra in terms of pollutant concentration using regression analysis based on previous calibration data. The instrument is optically simple, but due to the poor spectral resolution the data interpretation can be difficult even with the help of the on-line computer.

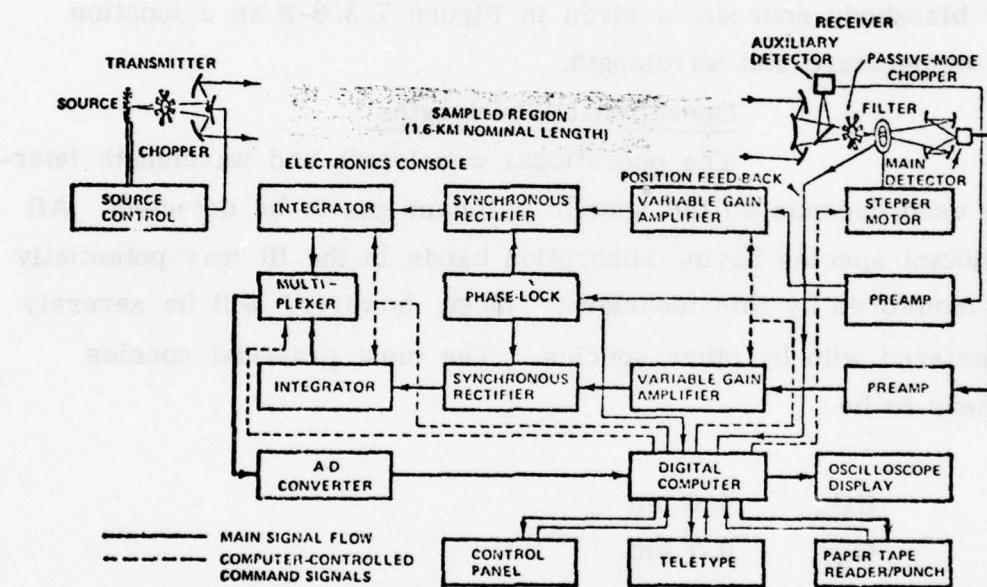


Figure 7.3.8-1. Block Diagram of the Bendix Filter-wheel Radiometer (Ref. 180).

### 7. 3. 8. 3 System Parameters

#### Source

Numerous commercial radiant sources are available which approximate the blackbody function over the infrared wavelength interval of interest. Temperatures available range to 1800K; 1100K is typical. Higher temperatures may not provide the expected signal improvement as they may necessitate a decrease in the instrument A  $\Omega$  parameter. Spectral radiance for blackbody sources is given in Figure 7. 3. 8-2 as a function of temperature and wavelength.

#### Operational Wavelengths

The operational wavelength and wavelength interval used depends on the specific pollutant gas to be detected. All pollutant species having absorption bands in the IR may potentially be monitored by this technique. Most, however, will be severely interfered with by other species. The most practical species appear to be

CO	4. 6 $\mu\text{m}$
O <sub>3</sub>	9. 7 $\mu\text{m}$

The following table illustrates the extent of the interference which may exist, depending on the exact wavelength intervals chosen.

Table 7. 3. 8-1. Pollutants and Interfering Species (Ref. 270)

Pollutant $\lambda$ ( $\mu\text{m}$ )	Interfering Species						
	CO <sub>2</sub>	CO	H <sub>2</sub> O	N <sub>2</sub> O	CH <sub>4</sub>	O <sub>3</sub>	HDO
CO <sub>2</sub> 2.1			X				
CO 4.6	X		X	X		X	
CO 2.3			X		X		X
SO <sub>2</sub> 8.6			X	X	X	X	X
SO <sub>2</sub> 4.0				X			
NO <sub>2</sub> 7.6			X	X	X		X
NO <sub>2</sub> 3.4			X		X		
NH <sub>3</sub> 10.5	X		X	X		X	
NH <sub>3</sub> 3.3	X		X	X	X		
NO 5.3	X	X	X				
HCHO 3.5			X	X	X		
HCl 3.3	X		X	X	X		
HF 2.7	X		X				
H <sub>2</sub> S 3.9				X			
HNO <sub>3</sub> 11.0	X		X	X			
CH <sub>4</sub> 8.0			X	X			

**7. 3. 8. 3c**

**Detector**

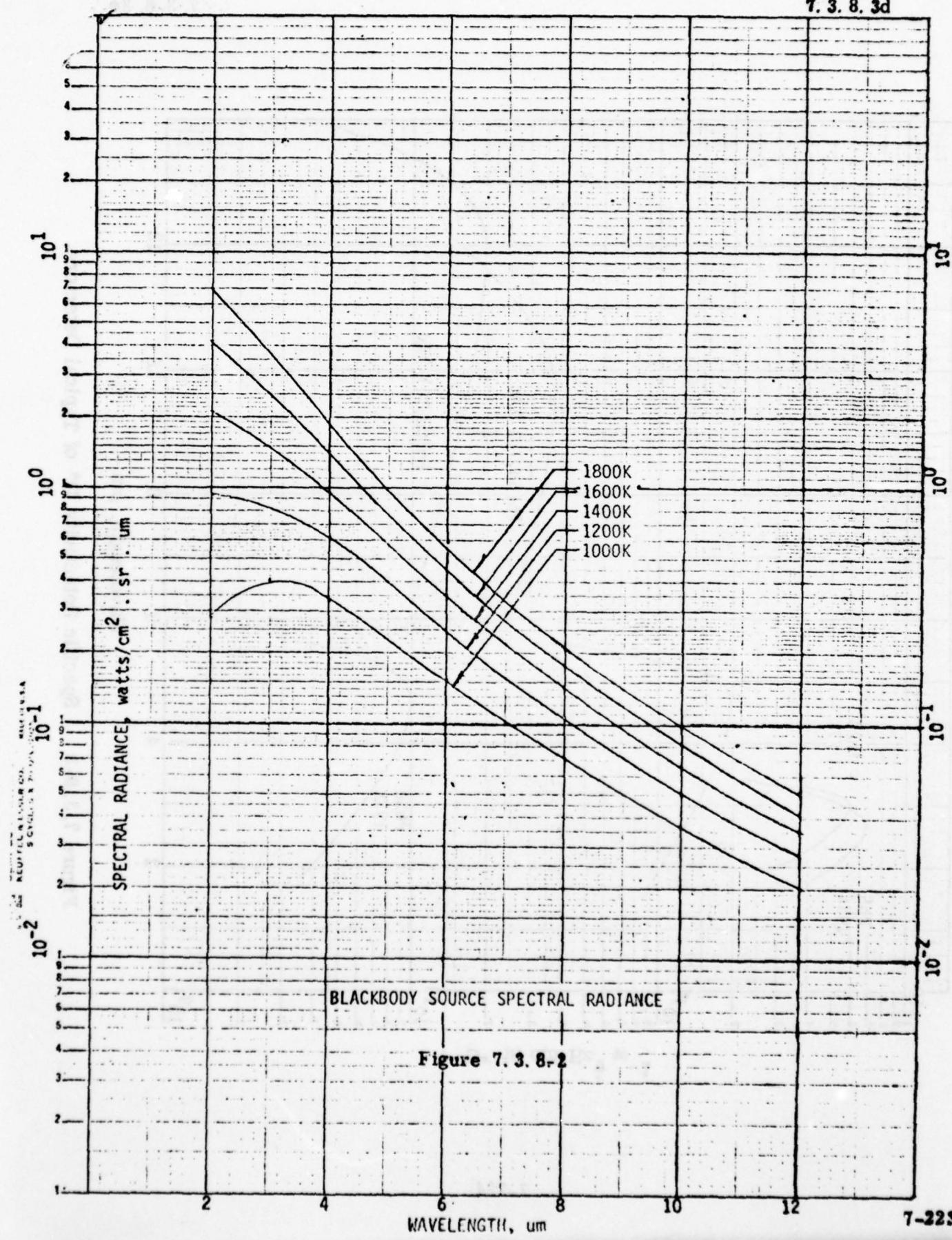
Commercially available detectors having the highest specific detectivity ( $D^*$ ) at these wavelengths are

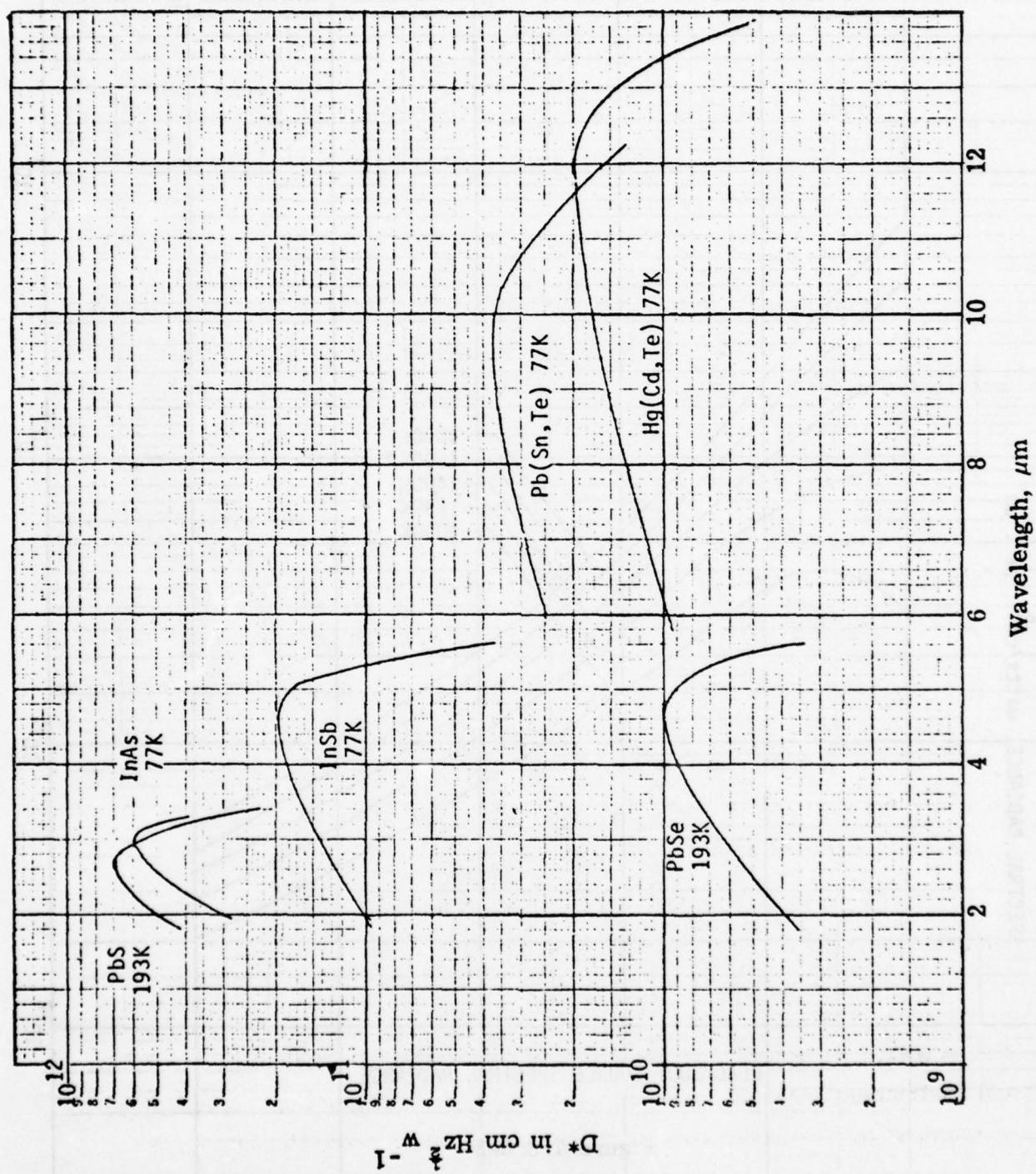
4. 6  $\mu\text{m}$ : Indium antimonide, InSb

9. 7  $\mu\text{m}$ : Lead Tin Telluride, Pb(Sn, Te)

Typical values of  $D^*$  for these and other detectors are shown in figure 7. 3. 8-3.

7.3.8.3d



Figure 7.3.8-3 Specific Detectivity  $D^*$  of Typical Detectors.

### Optics

Entrance aperture,  $A_o$  ( $\text{cm}^2$ )

Entrance solid angle,  $\Omega_o$  (steradians)

Optical efficiency,  $\eta_o$  (net transmission)

These optical parameters are chosen by the designer to optimize the system performance.

### Electronics

Electronic efficiency,  $\eta_e$

The electronic efficiency is the reduction in signal-to-noise due to the data processing. It may be appreciably less than unity even for a detector-noise-limited system.

Electronic Bandpass,  $\Delta_f$

Generally  $\Delta_f = 1/4t_c$  where  $t_c$  is the 0-63% time constant of the system readout, however, this can vary with electronics design.

### 7. 3. 8. 4 Theoretical Performance Prediction

Based upon known or assumed system parameters, an approximate performance prediction can be made. The accuracy of these calculated results will be dependent on the accuracies of the parameter values used and on the degree to which the system design conforms to the assumed theoretical model.

From Appendix VII, the signal-to-noise ratio for a filterwheel radiometer system is:

$$\text{SNR} = P/dP$$

The numerator,  $P$ , contains the source function, the modulation function and instrument optical performance terms. The denominator  $dP$  is the instrument performance limitation assuming optimized detector-noise-limited operation.

7.3.8.4b

where:  $P = N^0(\lambda, T)\Delta\lambda A_0 \Omega_0 \eta_0 M$

$$dP = NEP/\eta_e = (A_d/4\tau)^{1/2}/(\eta_e D^*)$$

and:  $N^0$  = Source spectral radiance, normally a blackbody  
is assumed. See Figure 7.3.8-2.  
Units: watts/cm<sup>2</sup> micron-steradian.

$\Delta\lambda$  = Wavelength interval defined by the optical filter.  
Units: microns

$A_0$  = Area of entrance optics. Units: cm<sup>2</sup>.

$\Omega_0$  = Solid angle of field of view.  
Units: steradians

$A_d$  = Area of detector. Units: cm<sup>2</sup>  
If not known, may be approximated by  $1.59 A_0 \Omega_0$

$\eta_0$  = Optical efficiency. Use 0.1\* unless otherwise  
known. Units: none

$t_c$  = System time constant, 0-63% response.  
Units: seconds

$\eta_e$  = Data processing efficiency. Use 0.3\* unless  
otherwise known.  
Units: none

$D^*$  = Detector specific detectivity. Use value from  
Figure 7.3.8-3 unless otherwise known.  
Units: cm Hz<sup>1/2</sup>/watt

NEP = Noise-equivalent power. Units: watts.  
When quoted in system specification, NEP may have  
units of watts/Hz<sup>1/2</sup>; if so, divide given value by  
 $\sqrt{4t_c}$  before using.

\*Typical values for well-designed systems.

7. 3. 8. 4c

M = Modulation factor. Exact calculation requires knowledge of the molecular spectral band parameters. If we assume that the intensity of the source is the same at the off-band and on-band measured wavelengths, the modulation factor becomes

$$M = 1 - \exp(-kcR(1+kcR/4a)^{-\frac{1}{2}})$$

where k = band-averaged absorption coefficient Units:  
 $\text{cm}^{-1} \text{ atm}^{-1}$

where a = band-averaged fine structure parameter Units:  
none

c = Fractional concentration of pollutant in atmosphere  
being monitored, i. e., ppm  $\times 10^{-6}$

R = Optical path length in atmosphere being monitored.  
Units: cm.

Values of k and a can be obtained from NASA CR-2324 (Reference 180).

Calculation Procedure:

We can approximate the modulation factor as

$$M = 1 - \exp(-\bar{k}cR)$$

and the signal-to-noise equation becomes

$$\text{SNR} = 2N^0 \Delta \lambda A_o \eta_o \eta_e D^* M \sqrt{\tau} / \sqrt{A_d}$$

SNR values will generally be quite high with this type of instrument. The measurement should not be assumed to be accurate to better than 0.01 ppm.

Analytical Determination of SNR

The above equation can be used to calculate a predicted value of SNR. Unless otherwise known the following values can be assumed for the variables defined above:

$A_o$  = area of entrance optics

$\Omega_0$  = solid angle of field of view; approximately  $(r/R)^2$ , where  $r$  = width of field of view at  $R$  distance. For example, if 1 meter ( $=r$ ) field of view at 100 meters ( $=R$ ) distance,  $\Omega_0 = 10^{-4}$  steradians.

$N^0$ : assume Figure 7.3.8-2

$\Delta\lambda$ : assume  $0.05 \mu\text{m}$  (typical value for well-designed system)

$A_d$ : assume  $1.59 A_o \Omega_0$

$\eta_o$ : assume 0.1

$\eta_e$ : assume 0.3

$D^*$ : assume Figure 7.3.8-3

$k$ : assume  $0.014 \text{ cm}^{-1} \text{ atm}^{-1}$  for CO at  $4.6 \mu\text{m}$

assume  $0.021 \text{ cm}^{-1} \text{ atm}^{-1}$  for  $O_3$  at  $9.7 \mu\text{m}$

$t_c$ : instrument time constant, seconds

$c$ : concentration,  $\text{ppm} \times 10^6$

$R$ : range, cm

it is convenient to calculate SNR in two steps.

$$\text{SNR} = G (M/\tau)$$

7. 3. 8. 4e

where  $G = 2N^0 \Delta\lambda A_o \Omega_o \eta_e D^* / \sqrt{A_d}$

$$M = 1 - \exp(-kcR)$$

Step 1: Calculate G

Use known experimental values or approximate values given above.

This value of G can now be used for various values of c, R, and  $\tau$ , which are often field variables.

Step 2: Calculate SNR =  $G (1 - \exp(-kcR)) \sqrt{t_c}$

Use various anticipated field values of c, R and  $\tau$ . Use values of k given above.

#### Graphical Determination of SNR

We assume the following typical values

$$A_o = 500 \text{ cm}^2$$

$$\Omega_o = 10^{-4} \text{ sr}$$

$$N^0 = 0.5 \text{ watt cm}^{-2} \text{ sr}^{-1} \mu\text{m}^{-1} \text{ at } 4.6 \mu\text{m (CO)}$$

$$0.05 \text{ watt cm}^{-2} \text{ sr}^{-1} \mu\text{m}^{-1} \text{ at } 9.7 \mu\text{m (O}_3\text{)}$$

$$\Delta\lambda = 0.05 \mu\text{m}$$

$$A_d = 1.59 A_o \Omega_o \text{ cm}^2$$

$$\eta_o = 0.1$$

$$\eta_e = 0.3$$

$$D^* = 10^{11} \text{ cm HI}^{\frac{1}{2}} \text{ w}^{-1}$$

We leave the quantities c, R, and  $t_c$  as variables.

Step 1: Calculate:  $M = 1 - \exp(-kcR)$

7. 3. 8. 4f  
7. 3. 8. 6a

Assume: Value of pollutant concentration, ppm

Range, meters

Result: Figure 7. 3. 8-4 gives M for CO and  $O_3$  as a function of c and R.

Step 2: Calculate:  $SNR = GM/\sqrt{t_c}$

Assume: Value of G based on assumed experimental values above.

$t_c$ , time constant, seconds

M. modulation factor, from Step 1

Result: Figure 7. 3. 8-5 and 7. 3. 8-6 give values of SNR for, respectively, CO and  $O_3$  for values of M and  $t_c$ .

#### 7. 3. 8. 5 Special Performance Requirements

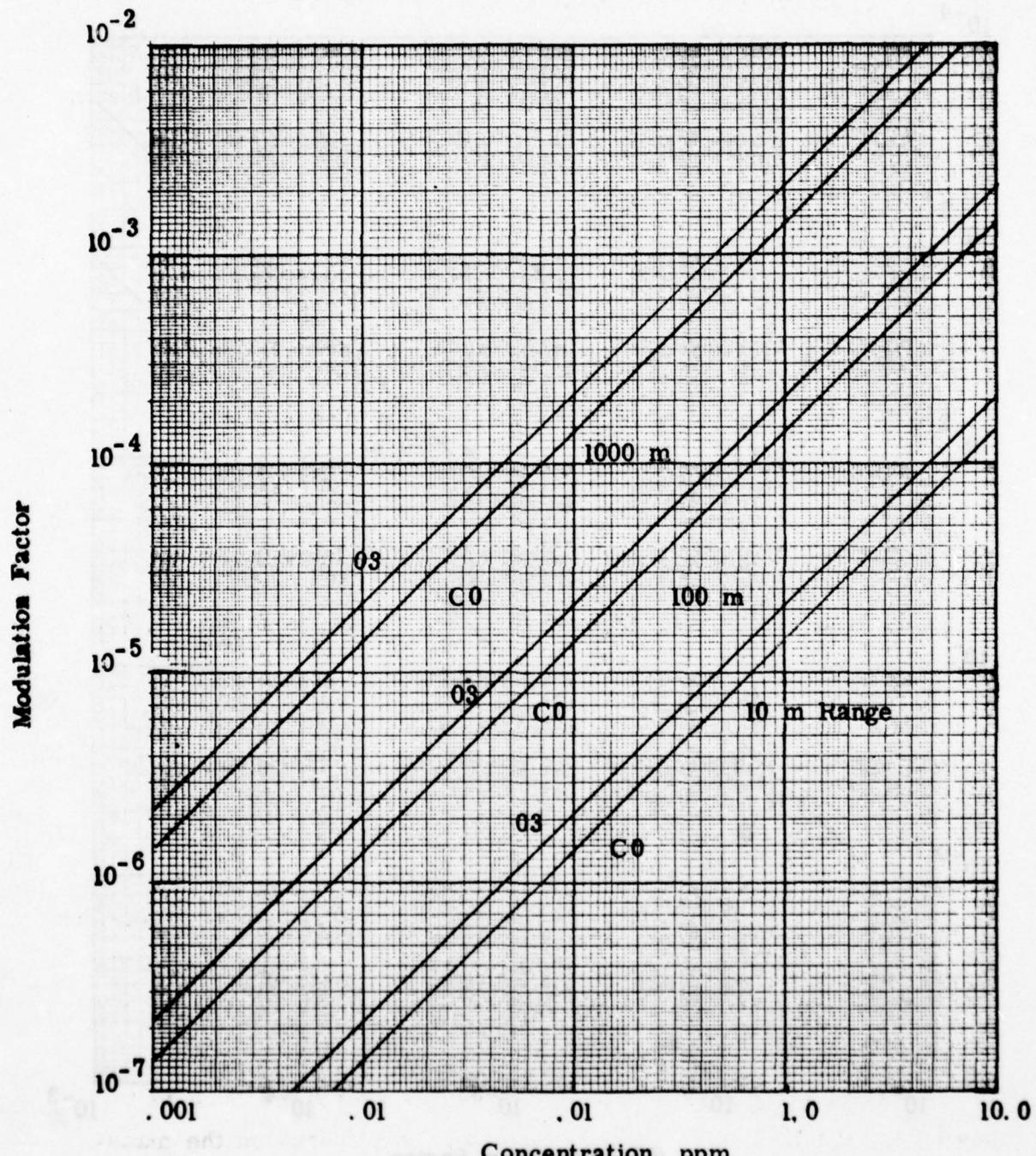
The non-special requirements were discussed in Section 7.1, Procedures Applicable to All Remote Sensors.

In general, no special requirements are required by radiometers. Special requirements due to a particular instrument design should be noted by the manufacturer.

#### 7. 3. 8. 6 Data Analysis Procedure

In its simplest form, data analysis is performed by comparing the experimental data with an empirically determined calibration curve. This can result in large errors due to spurious signals caused by overlapping absorption bands of other species.

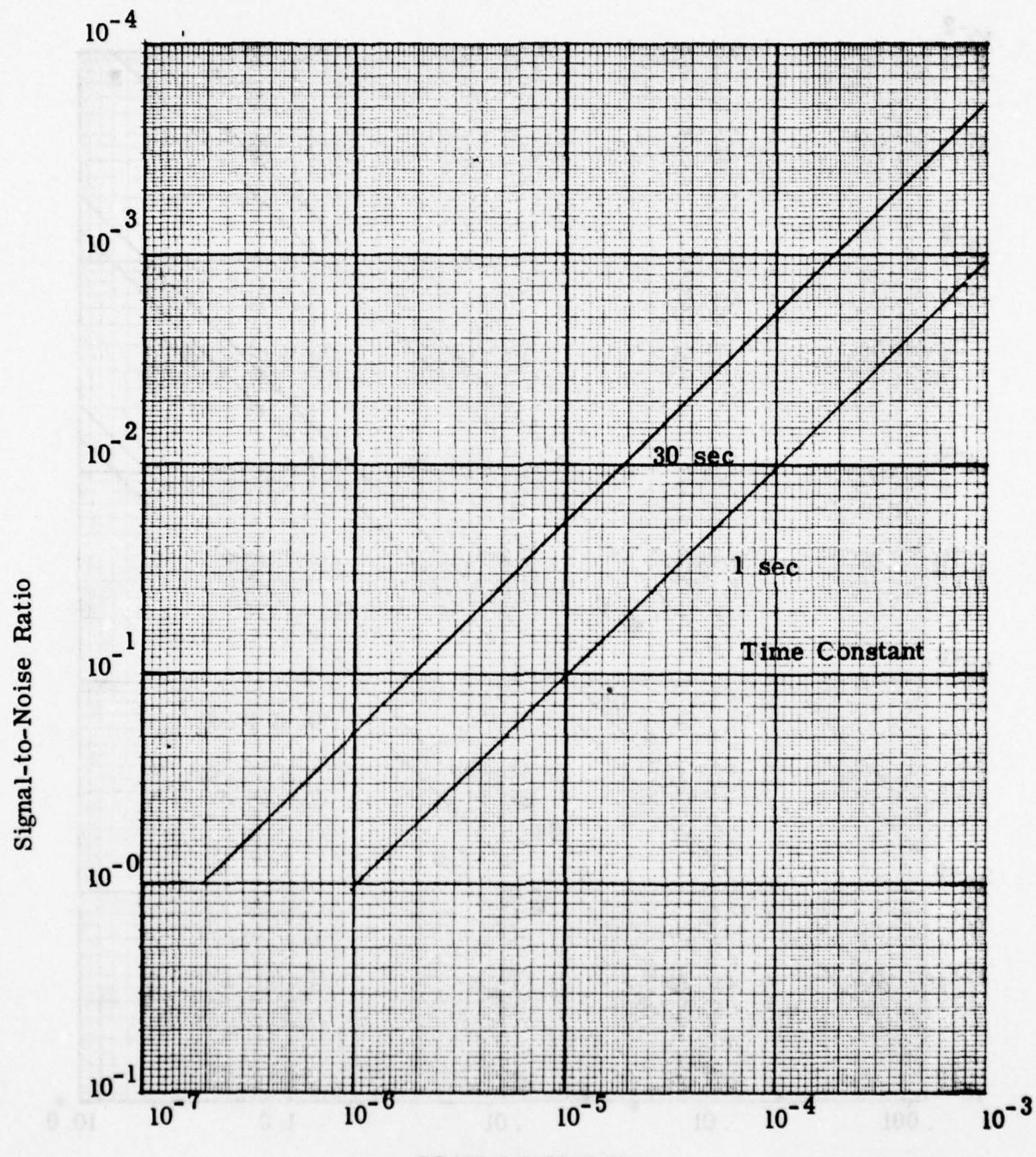
The analysis procedure to correct this problem must be detailed by the instrument manufacturer and will depend on the manufacturer's ingenuity, the exact wavelengths at which the measurements



Graphical Analysis - Step 1

Figure 7. 3. 8-4

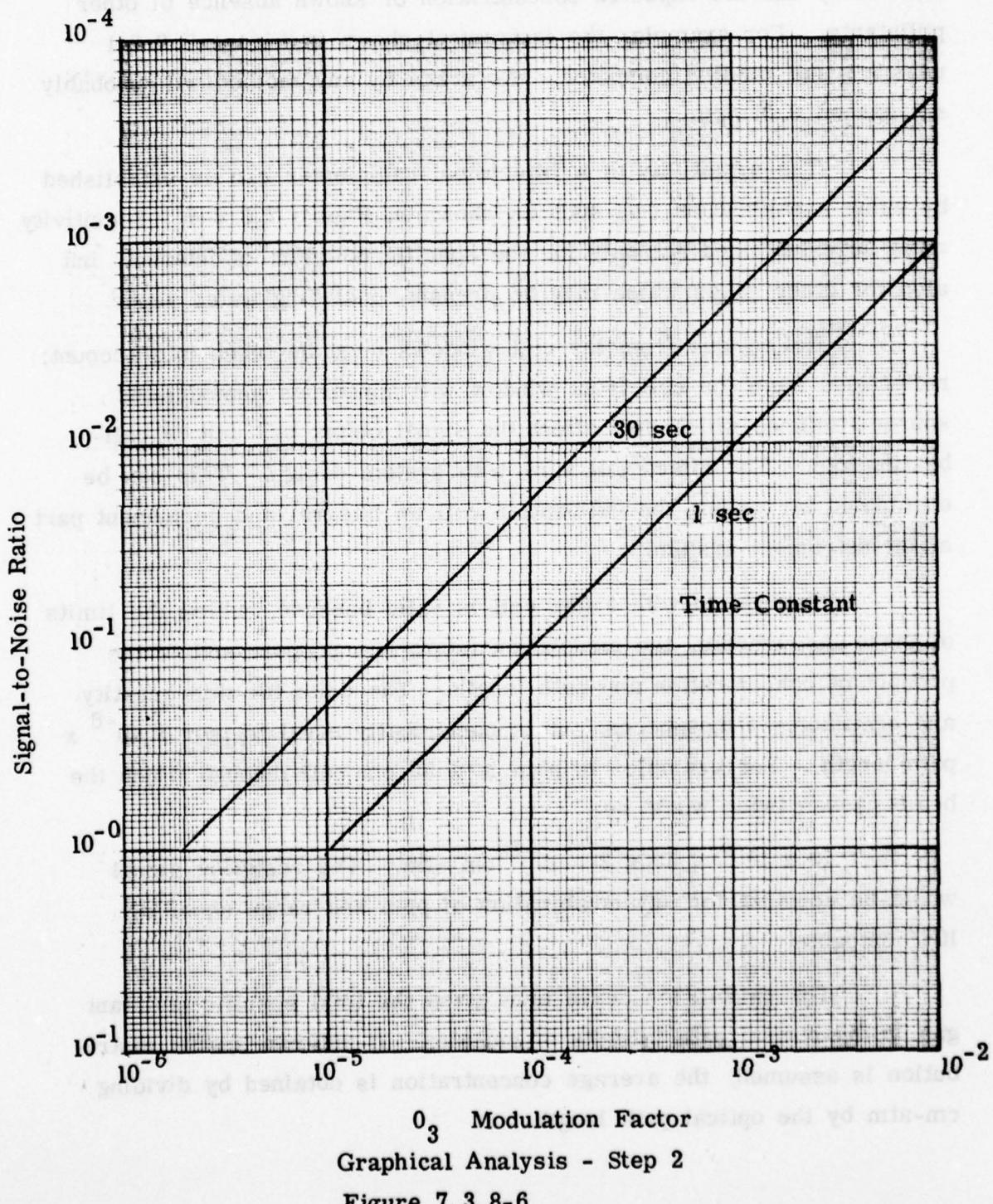
7. 3. 8. 6c



C<sub>0</sub> Modulation Factor  
Graphical Analysis - Step 2

Figure 7. 3. 8-5

7.3.8.6d



7.3.8.6e

are taken, and the expected concentration or known absence of other pollutants. For example, the instrument shown in Figure 7.3.8-1 uses a small on-line computer. Accuracy by any method will probably not exceed 0.01 ppm.

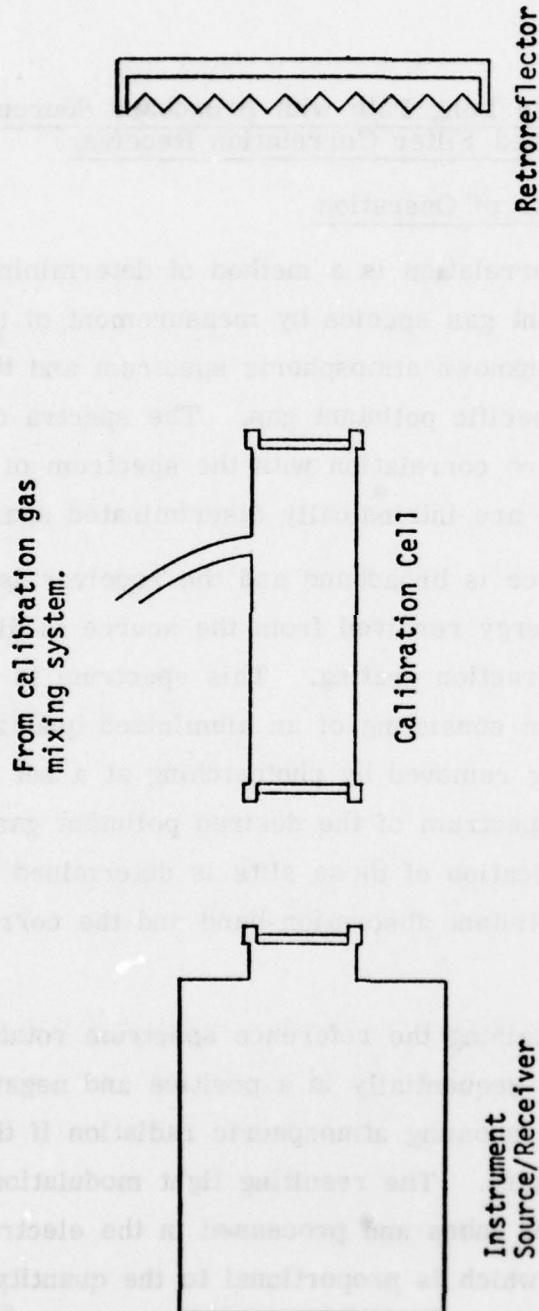
The sensitivity of a filterwheel radiometer can be established by using a calibration cell such as shown in Figure 7.3.8-7. Sensitivity must be established not only for the specific pollutant of interest, but also for other gases which may be present, including water vapor.

Reflections from the cell windows must be taken into account; reflections from the cell front window will appear as unmodulated source radiance which may affect the signal output per unit of calibration gas. The effect will vary with system design. This can be eliminated by making the calibration cell an integral and permanent part of the instrument system.

Calibration with a gas cell is valid because, within the limits of these instruments, the modulation (signal) is proportional to the product of concentration and path length. The units for this quantity are centimeter-atmospheres. It is numerically equal to  $\text{ppm} \times 10^{-6} \times$  path length. For example, 10 ppm in a 50 cm cell through which the beam passes twice would be:

$10 \times 10^{-6} \times 50 \times 2 = 10^{-3}$  cm atm. The resulting signal would be constant for any combination of ppm and range equalling  $10^{-3}$  cm atm.

The calibration curve thus gives the total specific pollutant gas in the optical path in units of cm-atm. If uniform spatial distribution is assumed, the average concentration is obtained by dividing cm-atm by the optical path length.



## CALIBRATION SYSTEM

Figure 7.3.8-7

7. 3. 9 UV/Visible Long Path with Broadband Source  
and Matched Filter Correlation Receiver

7. 3. 9. 1 Principle of Operation

Matched filter correlation is a method of determining the concentration of a pollutant gas species by measurement of the correlation between the unknown atmospheric spectrum and the known spectrum of the specific pollutant gas. The spectra of other gases have near zero correlation with the spectrum of this particular species and so are intrinsically discriminated against.

The radiant source is broadband and the receiver is dispersive. The radiant energy received from the source is dispersed into a spectrum by a diffraction grating. This spectrum is focused onto a reference spectrum consisting of an aluminized quartz disk with the aluminum coating removed by photoetching at a set of precise wavelengths in the spectrum of the desired pollutant gas species. The spectral width and location of these slits is determined by computer modelling of the pollutant absorption band and the correlation process.

As this disk containing the reference spectrum rotates, the slit arrays will correlate sequentially in a positive and negative sense with the spectrum of the incoming atmospheric radiation if that species is present in the atmosphere. The resulting light modulations are detected by photomultiplier tubes and processed in the electronics to produce a voltage output which is proportional to the quantity (ppm-meters) of the pollutant in the measured path.

In principle, this technique is similar to gas filter correlation, described in 7. 3.7 and 7. 3.10 of this report, except that gas filter correlation uses a sample of the gas as a wavelength-selective absorber in a nondispersive optical system.

#### 7. 3. 9. 2 System Description

The system consists of a source and a receiver. The source may be at the opposite end of the test region, or it may be adjacent to the receiver and a retroreflector used to define the test region extremity. In this latter case the sensitivity is increased because the path length through the atmosphere is doubled.

The source must be chopped to provide a means by which the electronics can discriminate against the spurious signal component due to scattered and reflected sunlight, which can be strong at these wavelengths.

Figures 7. 3. 9-1 and -2 are the schematic and photograph of a matched filter instrument. The specific instrument shown is designed to measure two gases simultaneously and so contains two diffraction gratings and detectors.

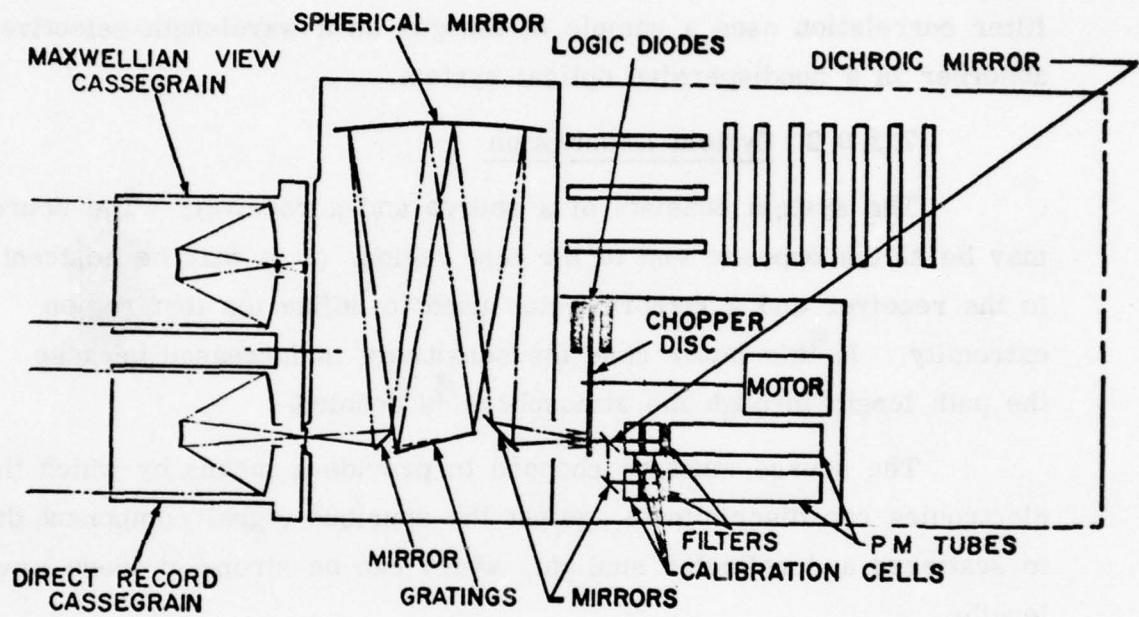


Figure 7. 3. 9-1. Matched Filter Correlation Instrument Diagram,  
Dual Gas Model

7.3.9.2c

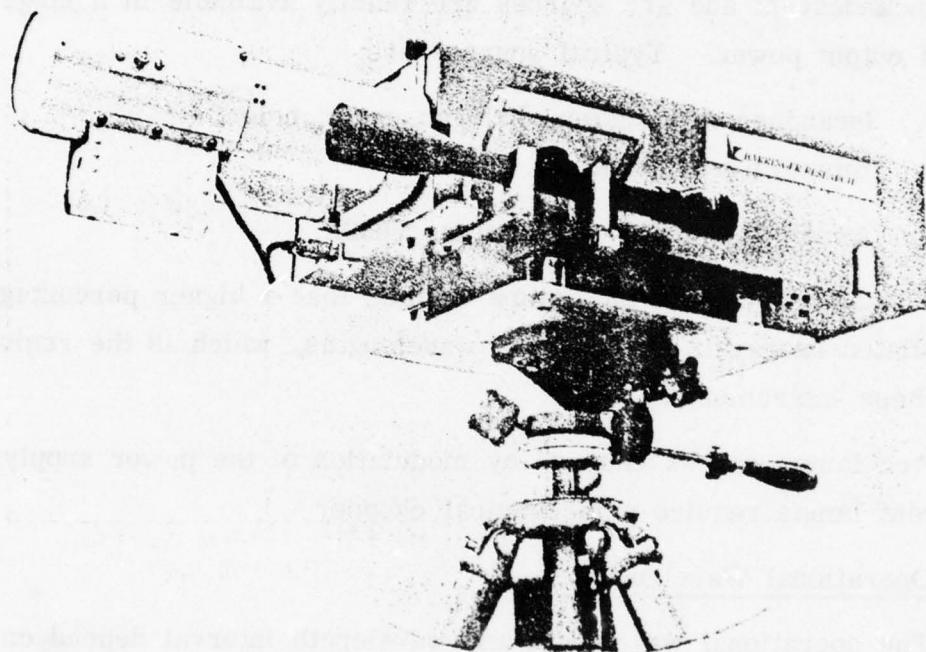


Figure 7.3.9-2. Matched Filter Correlation Instrument

### 7. 3. 9. 3. System Parameters

#### Source

Incandescent and arc sources are readily available in a large variety of output power. Typical sources are:

1. Incandescent tungsten, halogen cycle; color temperature 3000K.
2. Xenon arc; color temperature 6000K.

The higher color temperature implies that a higher percentage of the radiated energy is in the short wavelengths, which is the region used by these instruments.

Arc lamps can be chopped by modulation of the power supply; incandescent lamps require a mechanical chopper.

#### Operational Wavelengths

The operational wavelength and wavelength interval depend on the specific pollutant gas to be detected.

Not all pollutants are suitable for matched filter correlation detection. To date, the measurement of two gases have been shown to be feasible by this technique:

$\text{SO}_2$       280-315 nm

$\text{NO}_2$       413-450 nm

#### Detector

Photomultiplier tubes are the detectors best suited for this wavelength region. Many varieties are available for optimizing the instrument design. Those having an S-5 response function have peak

7. 3. 9. 3b  
7. 3. 9. 4a

response in these wavelength regions, although other response functions may be better suited to a particular instrument.

### Optics

Entrance aperture,	$A_o$ ( $\text{cm}^2$ )
Entrance solid angle,	$\Omega_o$ (steradians)
Optical efficiency,	$\eta_o$ (net transmission)

These optical parameters are chosen by the designer to optimize the system performance.

### 7. 3. 9. 4. Theoretical Performance Predictions

Based upon known or assumed system parameters, an approximate performance prediction can be made. The accuracy of these calculated results will be dependent on the accuracies of the parameter values used and on the degree to which the system design conforms to the assumed theoretical model.

From Appendix VII, the signal-to-noise ratio for a matched filter correlation system is:

$$\text{SNR} = P/dP$$

The numerator,  $P$ , contains the source function, the modulation function and instrument optical performance terms. The denominator  $dP$  is the instrument performance limitation assuming optimized operation.

7.3.9.4b

The signal for the matched filter correlation system is given by

$$P = \eta_o A_o \Omega_o N n \Delta \lambda M \lambda / hc$$

where

$\eta_o$  = optical efficiency

$A_o$  = entrance aperture

$\Omega_o$  = entrance solid viewing angle

N = source radiance

n = number of slits in reference spectrum

$\Delta \lambda$  = width of slits in reference spectrum

M = modulation coefficient; see below

$\lambda$  = center band wavelength

h = Planck's constant

c = speed of light

The modulation coefficient is given by

$$M = e^{-a_1 CR} - e^{-a_2 CR}$$

where

$a_1$  = average minimum atmospheric absorption coefficient across the slits.

$a_2$  = average maximum atmospheric absorption coefficient across the slits.

C = concentration

R = range

### 7. 3. 9. c

The system will in general be shot-noise limited with the noise level given by

$$dP = (\eta_o A_o \Omega_o N n \Delta \lambda M_1 \lambda / hc)^{1/2}$$

where

$$M_1 = (e^{-a_1} + e^{-a_2})/2$$

and the other quantities are as previously defined.

The signal-to-noise ratio is therefore

$$SNR = (\eta_o A_o \Omega_o N n \Delta \lambda \lambda / hc)^{1/2} (M/M_1)^{1/2}$$

#### Calculation Procedure

The values of SNR determined here are very high due to the ideal system assumed. In practice, the noise will be significantly higher due to interfering gas species, spectral structure in the source radiance and non-ideal instrument parameters.

#### Analytical Determination of SNR

For computational convenience only, the parameter IP is introduced.

Step 1: Calculate the instrument parameter:

$$IP = (\eta_o A_o \Omega_o N^o n \Delta \lambda \lambda / hc)^{1/2}$$

Typical values may be assumed. Known values are always to be preferred over these typical values.

$$\eta_o = 0.01$$

$$A_o = 100 \text{ cm}^2$$

$$\Omega_o = 10^{-5} \text{ steradians}$$

$$n \Delta \lambda = 15 \text{ nm}$$

$$N = 1.0 \text{ w/sr cm}^2 \text{ nm at } 300 \text{ nm (SO}_2\text{)}$$

$$N = 3.0 \text{ w/sr cm}^2 \text{ nm at } 430 \text{ nm (NO}_2\text{)}$$

$$\lambda/hc = 1.5 \times 10^{18} \text{ at } 300 \text{ nm}$$

$$\lambda/hc = 2.2 \times 10^{18} \text{ at } 430 \text{ nm}$$

Hence,

$$IP = 1.5 \times 10^7 \text{ for } SO_2$$

$$IP = 3.1 \times 10^7 \text{ for } NO_2$$

Step 2: Calculate the modulation parameter:

$$\left( \frac{M}{M_1^{1/2}} \right) = \frac{(e^{-a_1 CR} - e^{-a_2 CR}) 1.414}{(e^{-a_1 CR} + e^{-a_2 CR})^{1/2}}$$

Using the approximate gas parameter values:

$$a_1 = 7 \text{ cm}^{-1} \text{ atm}^{-1} \text{ for } SO_2$$

$$7 \text{ cm}^{-1} \text{ atm}^{-1} \text{ for } NO_2$$

$$a_2 = 10 \text{ cm}^{-1} \text{ atm}^{-1} \text{ for } SO_2$$

$$15 \text{ cm}^{-1} \text{ atm}^{-1} \text{ for } NO_2$$

These values of  $a_1$  and  $a_2$  are highly dependent on the particular instrument design.

The other parameters are the expected field values:

C = pollutant concentration, ppm  $\times 10^6$

R = measurement range, cm

Step 3: Calculate the anticipated signal-to-noise:

$$SNR = IP \left( \frac{M}{M_1^{1/2}} \right)$$

Graphical Determination of SNR

Step 1:      Calculate: Total pollutant in test path.  
 Assume: Known length of test path, meters.  
 Anticipated pollutant concentration, ppm.  
 Result: Plot in Figure 7. 3. 9-3 gives total pollutant  
 in units of cm-atm.

Step 2:      Calculate: Anticipated SNR.  
 Assume: Total pollutant in cm-atm (Step 1) assumed  
 typical instrument parameters as given in  
Analytical Determination of SNR.  
 Result: Plot in Figure 7. 3. 9-4 gives anticipated SNR  
 as a function of total pollutant.

Example: In Step 1 of the Analytical Determination of SNR, parameters  
 are given which are typical of a well-designed system. In the absence of ac-  
 tual instrument values, these typical values may be assumed. Using these  
 typical values, the parameter IP is calculated to be  $1.5 \times 10^7$  for  $\text{SO}_2$  and  
 $3.1 \times 10^7$  for  $\text{NO}_2$ . If actual values are known, this parameter should also  
 be calculated using the known values.

In Figure 7. 3. 9-4, the SNR curves assume the typical values  
 of IP. If actual values of IP are known, the SNR should be corrected as  
 follows:

$$\text{SNR (actual)} = \text{SNR (typical)} \frac{\text{IP (actual)}}{\text{IP (typical)}}$$

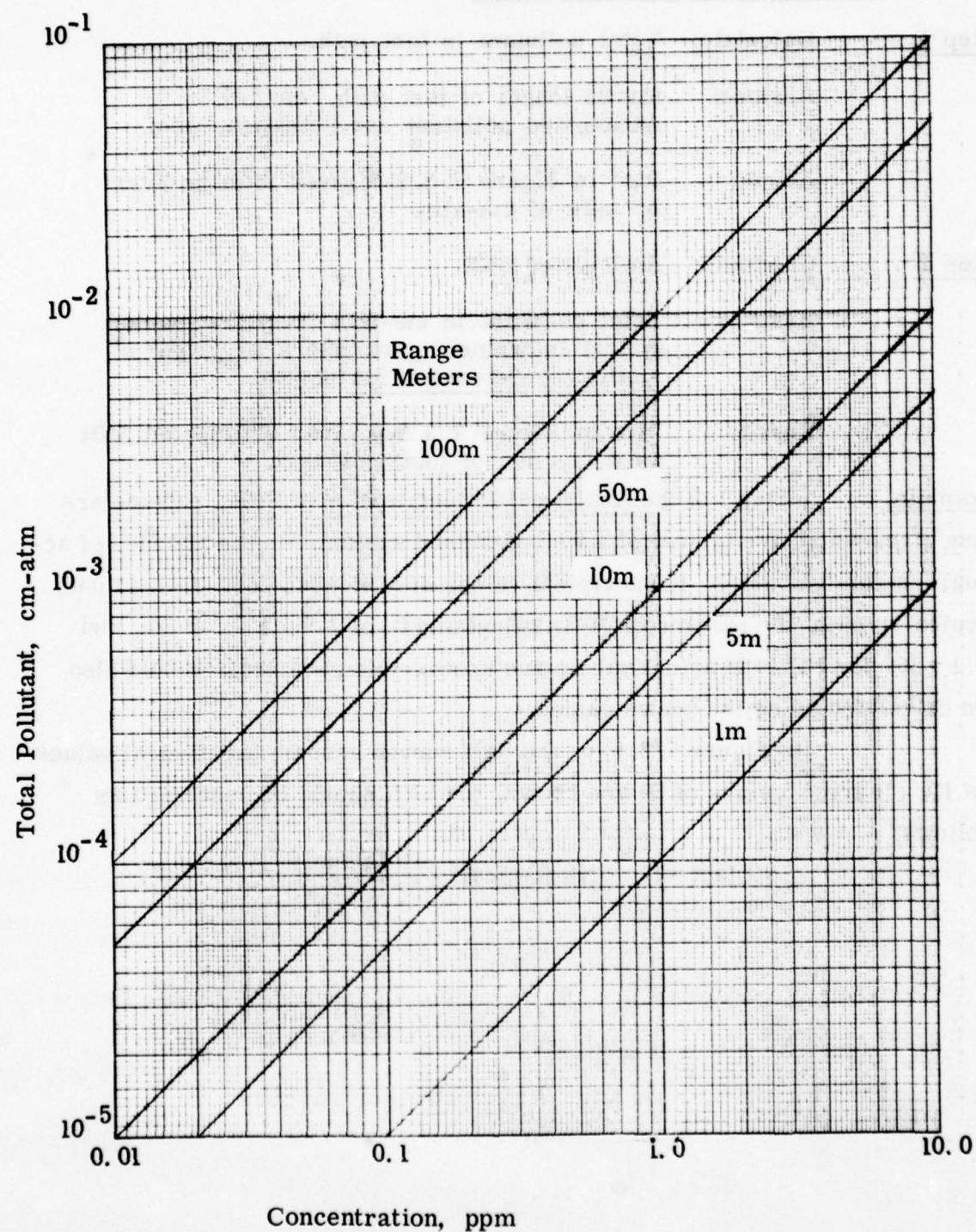


Figure 7. 3. 9-3. Graphical SNR Determination - Step 1

7. 3. 9. 4g

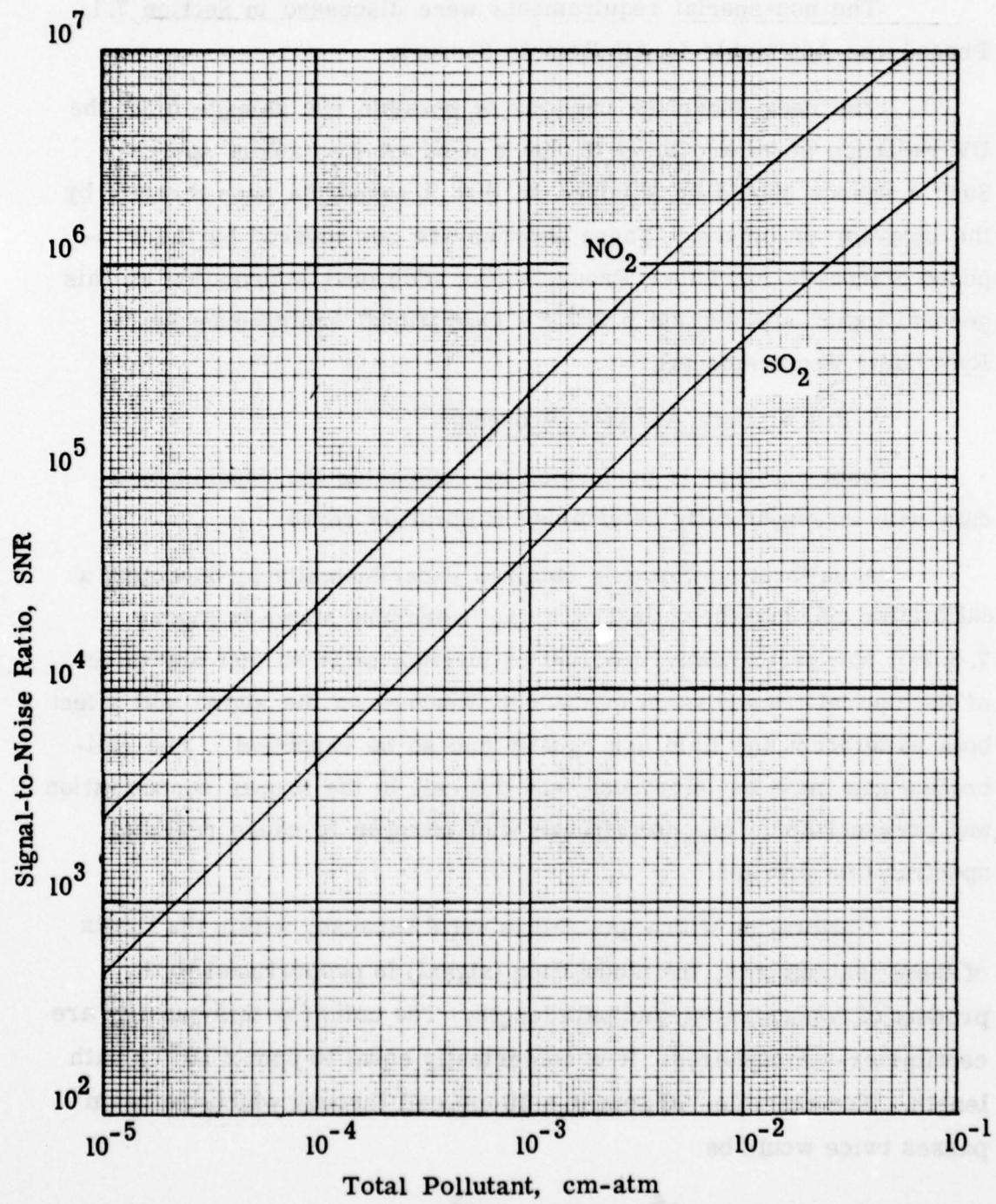


Figure 7. 3. 9-4. Graphical SNR Determination - Step 2

7.3.9.5  
7.3.9.6a

#### 7.3.9.5 Special Performance Requirements

The non-special requirements were discussed in Section 7.1, Procedures Applicable to All Remote Sensors.

The user should be cautious of possible eye damage from the UV radiation of an arc lamp if one is used as the radiant source. Such a source should be shielded so that it cannot be seen directly by the operator or others. These sources are not covered by the Proposed Standards for Laser Products (for additional information on this general topic, see Section 6.2.2.2 - Operational Limitations due to Eye Safety Requirements).

#### 7.3.9.6 Data Analysis Procedure

Data analysis is performed by comparing the experimental data with an empirically determined calibration curve.

A calibration curve is obtained experimentally by inserting a calibration cell into the optical path (the instrument shown in Figure 7.3.9-1 has permanently installed calibration cells so that any effect of the optical transmission of the cell windows on the signal will affect both calibration and field use equally and so be cancelled. The calibration gas must be introduced into the cell in the proper concentration and pressurized to one atmosphere with nitrogen to cause realistic spectral line profiles.

Calibration with a gas cell is valid because, within the limits of these instruments, the modulation (signal) is proportional to the product of concentration and path length. The units for this quantity are centimeter-atmospheres. It is numerically equal to ppm  $\times 10^{-3}$   $\times$  path length. For example, 10 ppm in a 50 cm cell through which the beam passes twice would be

$$10 \times 10^{-6} \times 50 \times 2 = 10^{-3} \text{ cm atm}$$

The resulting signal would be constant for any combination of ppm and range equaling  $10^{-3}$  cm-atm.

The calibration thus gives the total specific pollutant gas in the optical path in units of cm-atm. If uniform spatial distribution is assumed, the average concentration is obtained by dividing cm-atm by the optical path length.

Because of the uncertain path length due to scattering by atmospheric aerosols, the use of instruments operating at ultraviolet wavelengths may be limited in an airport environment to short range operation. Analysis of calibration accuracy in the presence of significant scattering is a very complex problem and depends on parameters values of the particular aerosol environment which are generally not known.

7. 3. 10 Passive Downward-Looking Monitor Using Gas Filter Correlation Receiver

This monitor was not found acceptable in the Selection and Ranking, Section 6. 2. 2. 1. The Data Validation section is included here because the discussion is pertinent to passive systems in general, in particular to the passive upward-looking systems of Section 7. 4.

7. 3. 10. 1 Principle of Operation

Gas filter correlation is a method of determining the concentration of pollutant gas species by measuring the correlation between the unknown atmospheric spectrum and the spectrum of a known sample of the specific pollutant gas which is contained in the instrument. The spectra of other gases have near zero correlation with the spectrum of this particular species and so are intrinsically discriminated against.

The radiant source is broadband and the receiver is non-dispersive. The radiant energy received from the source is passed alternately through the sample of the particular species and through a neutral absorber having the same total transmission as the gas sample. Radiation is absorbed in the gas cell only at those specific spectral line wavelengths which are characteristic of that gas species; in the neutral absorber radiation is absorbed equally at all wavelengths.

The difference in the source energy removed by the gas and the neutral absorber is the desired pollutant concentration signal. If the correlation coefficient between the spectra of the standard and the unknown is zero (random spectral line overlap) the same total energy will be removed from the beam by the neutral and the gaseous absorbers and no net signal results. If the correlation coefficient between the

spectra is plus unity (exact spectral line overlap) a signal will result. Little change will be observed in the source energy when transmitted through the gas cell because the exact wavelengths at which energy is selectively attenuated by the gas cell have already been attenuated by the pollutant, but the neutral absorber will attenuate the source energy non-selectively, resulting in a difference signal proportional only to the specific pollutant's absorption. This signal is related by calibration to the average concentration of the specific pollutant over the path between the source and receiver.

#### 7.3.10.2 System Description

A passive, down-looking system uses the naturally occurring infrared radiation of the ground or other terrain as the source of radiant energy. The receiver/detector is mounted in an aircraft and examines the source radiation after its absorption by the intervening atmosphere.

The integrated vertical column concentration of the pollutant species is measured instead of the horizontal concentration as did the previously described long-path bistatic systems.

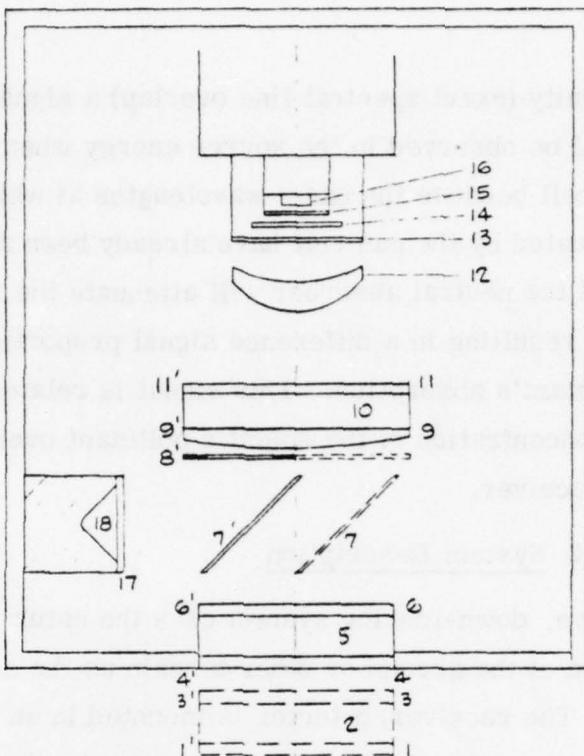
Such a system can quickly provide pollutant vertical column concentrations over a large grid defined by the aircraft flight pattern.

Schematic and detail drawings of a typical airborne instrument are shown in Figures 7.3.10-1 and 7.3.10-2. Figure 7.3.10-3 is a photograph of this instrument.

#### 7.3.10.3 System Parameters

##### Source

Because the terrain beneath the airborne instrument is the radiant source it is not under control of the experimenter but varies with the temperature and emissivity existing at the time and location at which data are required.



## Legend:

- 1, 1' Front window of external calibration cell
- 2 Gas in external calibration cell
- 3, 3' Rear window of external calibration cell
- 4, 4' Front window of internal calibration cell
- 5 Gas in internal calibration cell
- 6, 6' Rear window of internal calibration cell
- 7, 7' Chopper mirrors
- 8' Aperture
- 9, 9' Lens, serving as front window of gas cell
- 10 Gas in cell
- 11, 11' Rear windows of gas cell
- 12 Field lens
- 13 Window
- 14 Filter
- 15 Window of encapsulated detector
- 16 Detector
- 17 Window in front of calibration blackbody
- 18 Calibration blackbody at temperature T

Figure 7.3.10-1. Schematic of the GFC Instrument.

### 7.3.10.3c

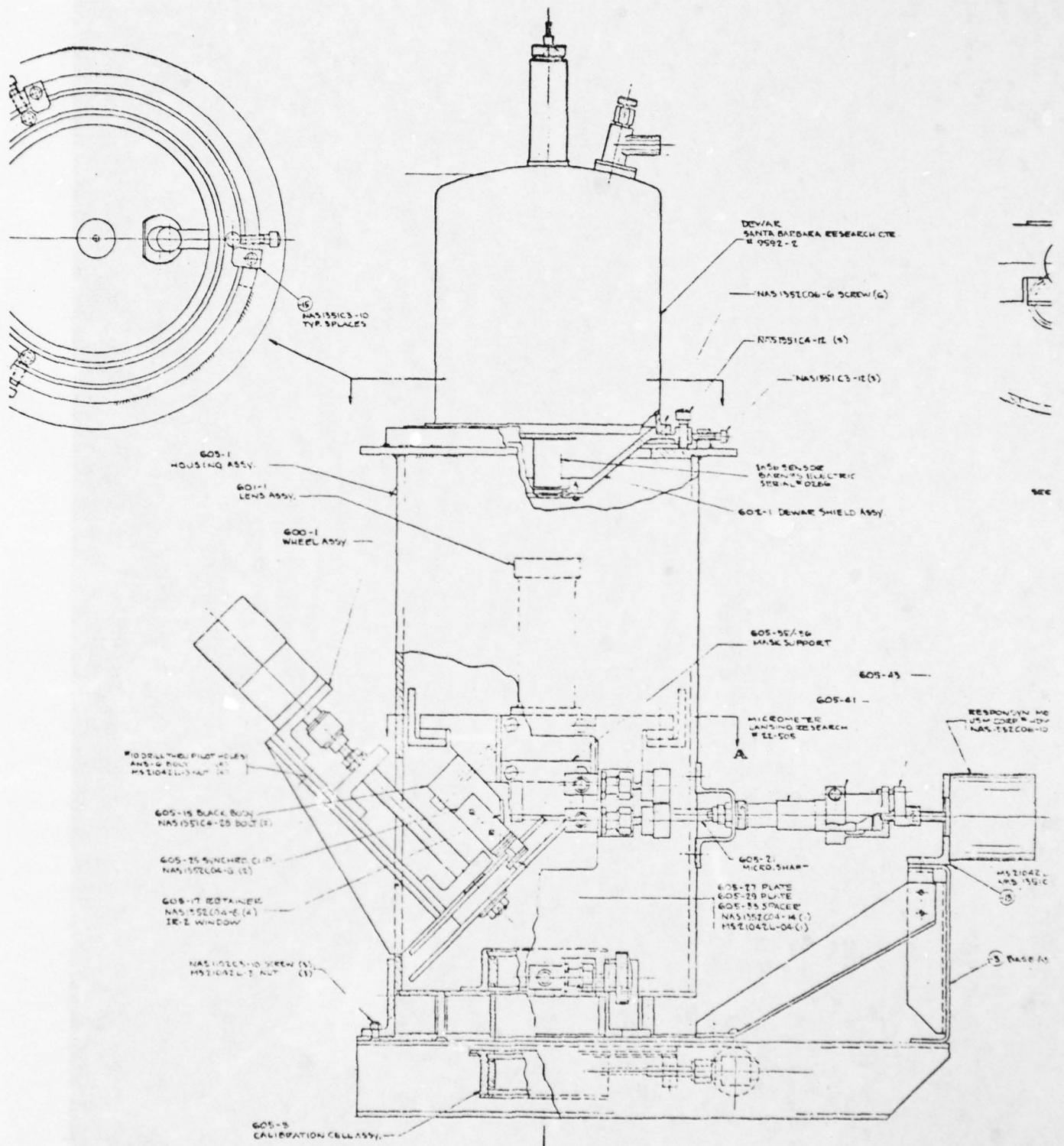


Figure 7.3. 10-2. GFC Instrument Assembly.

7.3.10.3d

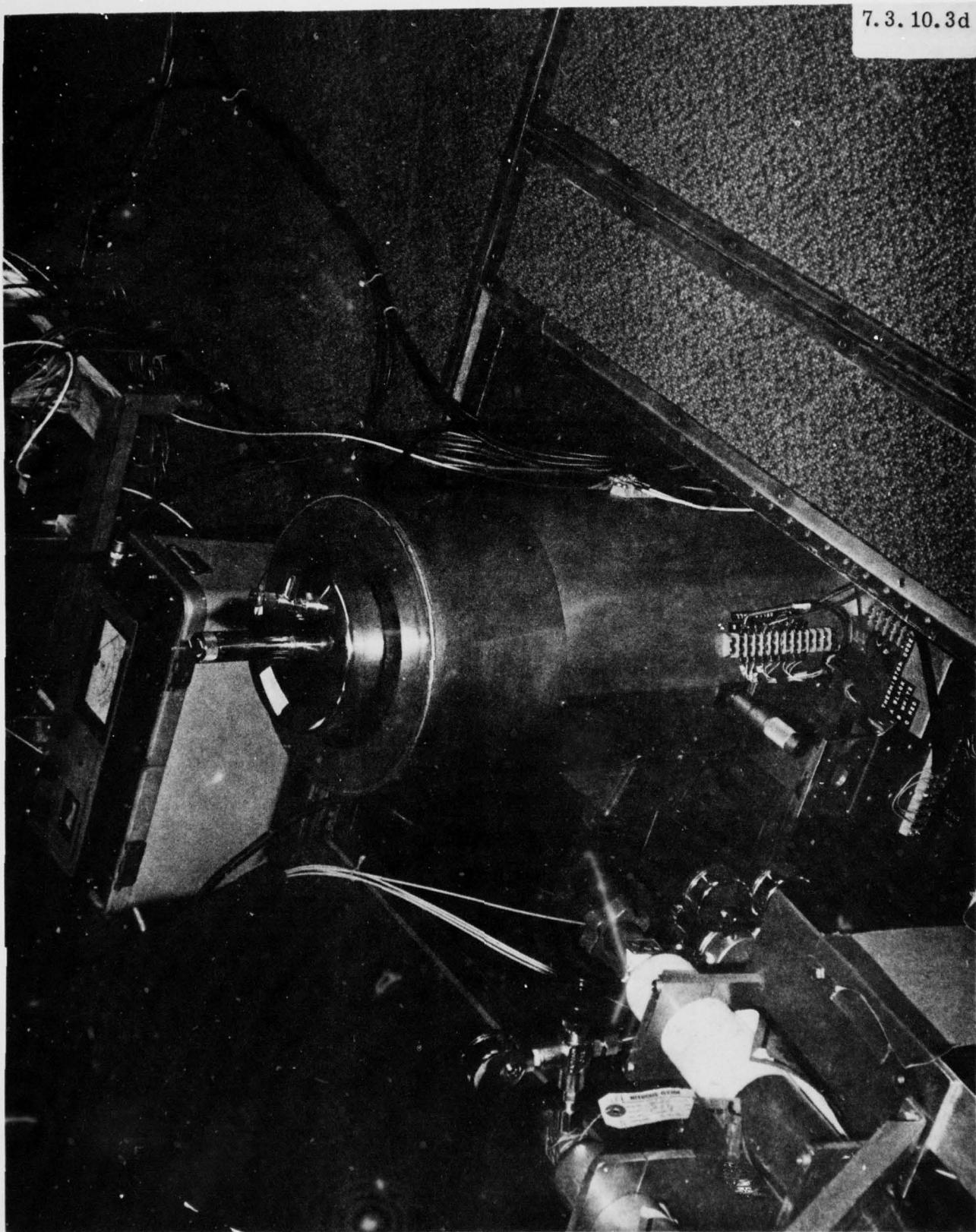


Figure 7.3.10-3. Photograph of GFC Instrument in Aircraft Bay.

Blackbody source spectral radiance curves are shown in Figure 7.3.10-4 for temperatures of 0°C, 20°C and 40°C. However, the actual terrain radiance will be less than this due to the emissivity of the particular surface. Typical values of emissivity are shown below and in Figure 7.3.10-5.

**Table 7.3.10-1. Reflectance ( $\rho$ ) and Emissivity ( $\epsilon$ ) of Common Terrain Features (Ref. 269).**

	0.7-1.0 $\mu$	1.8-2.7 $\mu$	3-5 $\mu$	8-13 $\mu$
Green Mountain Laurel	$\rho = 0.44$	$\epsilon = 0.84$	$\epsilon = 0.90$	$\epsilon = 0.92$
Young Willow Leaf (dry, top)	0.46	0.82	0.94	0.96
Holly Leaf (dry, top)	0.44	0.72	0.90	0.90
Holly Leaf (dry, bottom)	0.42	0.64	0.86	0.94
Pressed Dormant Maple Leaf (dry, top)	0.53	0.58	0.87	0.92
Green Leaf Winter Color - Oak Leaf (dry, top)	0.43	0.67	0.90	0.92
Green Coniferous Twigs (Jack Pine)	0.30	0.86	0.96	0.97
Grass - Meadow Fescue (dry)	0.41	0.62	0.82	0.88
Sand - Hainamamu Silt Loam - Hawaii	0.15	0.82	0.84	0.94
Sand - Barnes Fine Silt Loam - So. Dakota	0.21	0.58	0.78	0.93
Sand - Gooah Fine Silt Loam - Oregon	0.39	0.54	0.80	0.98
Sand - Vereiniging - Africa	0.43	0.56	0.82	0.94
Sand - Maury Silt Loam - Tennessee	0.43	0.56	0.74	0.95
Sand - Dublin Clay Loam - California	0.42	0.54	0.83	0.97
Sand - Pullman Loam - New Mexico	0.37	0.62	0.78	0.93
Sand - Grady Silt Loam - Georgia	0.11	0.58	0.85	0.94
Sand - Colts Neck Loam - New Jersey	0.28	0.67	0.90	0.94
Sand - Mesita Negra - lower test site	0.38	0.70	0.75	0.92
Bark - Northern Red Oak	0.23	0.78	0.90	0.96
Bark - Northern American Jack Pine	0.18	0.69	0.88	0.97
Bark - Colorado Spruce	0.22	0.75	0.87	0.94

### Operational Wavelengths

The operational wavelength and wavelength interval used depends on the specific pollutant gas to be detected. Typical wavelengths are:

CO	4.6 $\mu$ m
SO <sub>2</sub>	4.0 $\mu$ m, 8.7 $\mu$ m
NO	5.3 $\mu$ m
NO <sub>2</sub>	3.4 $\mu$ m
Hydrocarbons	3.5 $\mu$ m

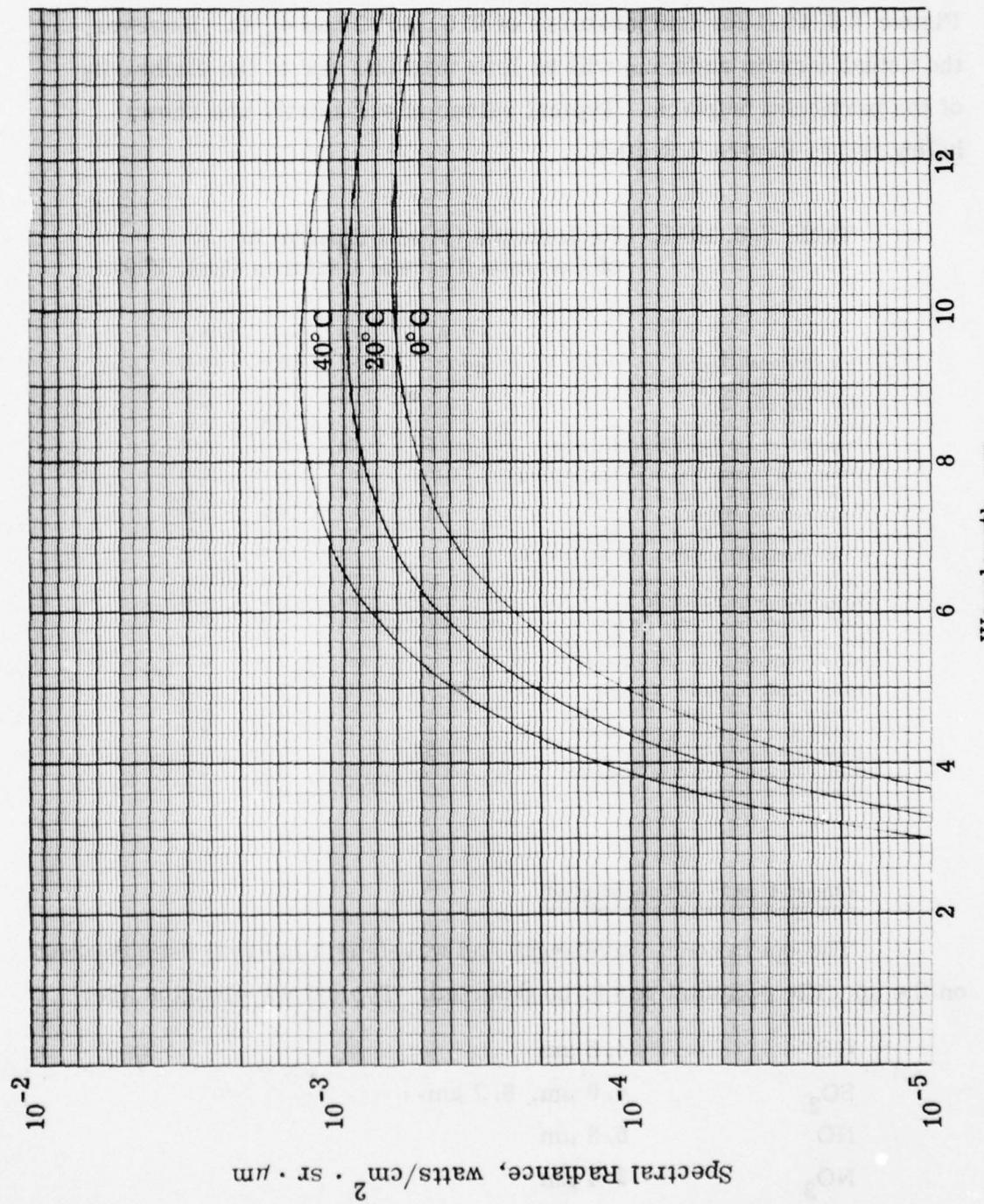
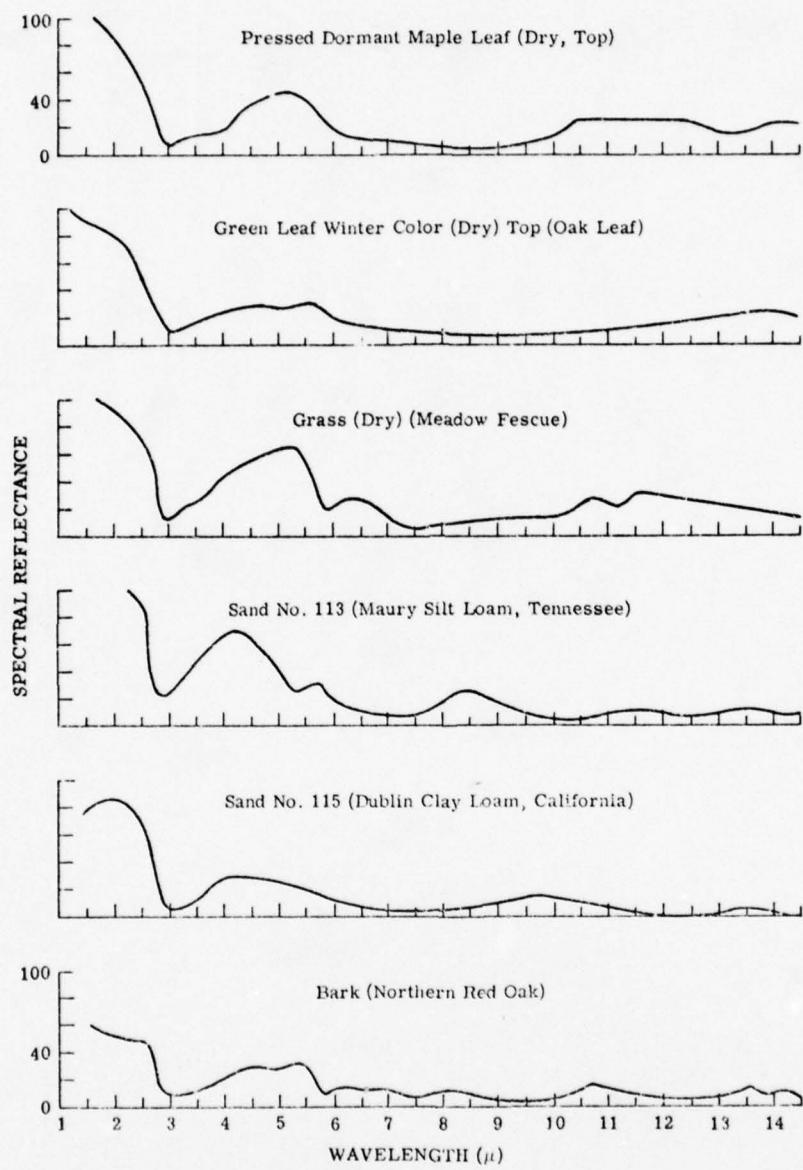


Figure 7.3.10-4. Blackbody Source Spectral Radiance.

**7.3.10.3g**



**Figure 7.3.10-5. Measured Values of Radiant Emissivity and Reflectance.**  
Emissivity = 1 - Reflectance (Reg. 269).

Wavelengths for other gases are selected on the basis of spectral band parameters and freedom from interfering species, especially water vapor. Not all pollutants are suitable for GFC detection.

#### Detectors

Some commercially available detectors, their operating temperature and their regions of optimum performance are:

PbS (193K)	2 - 3 $\mu\text{m}$
PbSe (193K)	2 - 5 $\mu\text{m}$
InSb ( 77K)	2 - 5 $\mu\text{m}$
Pb(Sn, Te) ( 77K)	5 - 10 $\mu\text{m}$
Hg(Cd, Te) ( 77K)	7 - 12 $\mu\text{m}$

Characteristic values of the parameters  $D^*$  for these detectors are shown in Figure 7.3.10-6.

#### Optics

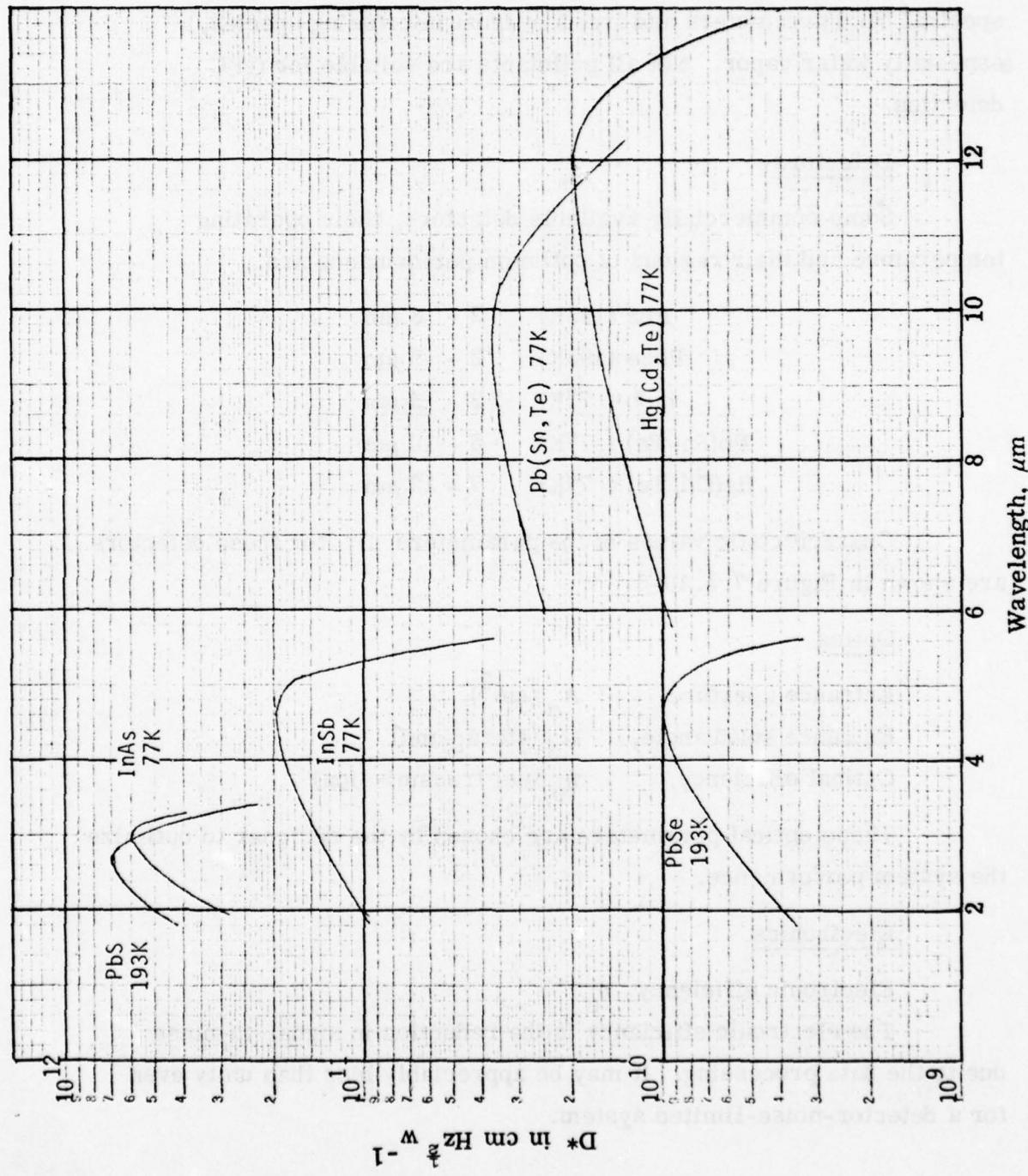
Entrance aperture,	$A_o$ ( $\text{cm}^2$ )
Entrance solid angle,	$\Omega_o$ (steradians)
Optical efficiency,	$\eta_o$ (net transmission)

These optical parameters are chosen by the designer to optimize the system performance.

#### Electronics

Electronic efficiency,  $\eta_e$

The electronic efficiency is the reduction in signal-to-noise due to the data processing. It may be appreciably less than unity even for a detector-noise-limited system.

Figure 7.3.10-6. Specific Detectivity  $D^*$  of Typical Detectors.

#### Electronic bandpass, $\Delta f$

Generally  $\Delta f = 1/4t$  where  $t$  is the 0-63% time constant of the system readout; however, this can vary with electronics design.

#### 7.3.10.4 Theoretical Performance Prediction

Based upon known or assumed system parameters, an approximate performance prediction can be made. The accuracy of these calculated results will be dependent on the accuracies of the parameter values used and on the degree to which the system design conforms to the assumed theoretical mode.

From Appendix VII, the signal-to-noise ratio for a gas filter correlation system is:

$$\text{SNR} = P/dP .$$

The numerator,  $P$ , contains the source function, the modulation function and instrument optical performance terms. The denominator  $dP$  is the instrument performance limitation assuming optimized detector-noise-limited operation.

For an airborne instrument an exact expression for the source function must include contributions from reflected sunlight, terrain emission and atmospheric emission. These are multiplied by the transmission of the atmosphere and are integrated over both altitude and wavelength to determine the exact radiant energy arriving at the instrument.

The following equation illustrates the exact solution for a single wavelength. In use, it must also be integrated with respect to wavelength over the wavelength interval of the instrument.

$$\begin{aligned}
 E(\lambda) = & \rho(\lambda) N(T_S, \lambda) \int_0^h \frac{\partial \tau(\lambda, Z)}{\partial Z} dZ \int_0^h \frac{\partial \tau(\lambda, Z)}{\partial Z} dZ \\
 & + \epsilon_G(\lambda) N^0(T_G, \lambda) \int_0^h \frac{\partial \tau(\lambda, Z)}{\partial Z} dZ \\
 & + \int_0^h \frac{\partial \tau(\lambda, Z)}{\partial Z} N^0[T(Z), \lambda] dZ
 \end{aligned}$$

where  $\rho(\lambda)$  is the reflectivity of the earth's surface,  $\tau'(\lambda)$  is the atmospheric transmission from the sun to the surface,  $\tau(\lambda)$  is the atmospheric transmission from the surface to the aircraft at altitude  $h$ ,  $T_S$  is the sun's temperature,  $\epsilon_G(\lambda)$  is the surface emissivity,  $T_G$  is the surface temperature,  $T(Z)$  is the atmospheric temperature at height  $Z$ . The transmissivity is given by

$$\tau(\lambda, Z) = \exp \left[ - \int_Z^h \sum_i k_i(\lambda, Z') C_i(Z') p_t(Z') dZ' \right]$$

where  $k_i(\lambda, Z)$  is the monochromatic absorption coefficient of species  $i$  at altitude  $Z$ ,  $C_i(Z)$  is the concentration of species  $i$  at altitude  $Z$ , and  $p_t(Z)$  is the total pressure at altitude  $Z$ .

The expressions can be simplified if several reasonable limitations are placed on the measurement parameters.

The first term in the above expression is due to reflected sunlight. This can be neglected if measurements can be constrained to the

longer wavelengths for which the sunlight term is small compared to the terrain radiance. It can be seen from Figure 7.3.10-7 that for  $\rho = 0.2$ ,  $\epsilon = 1 - \rho = 0.8$  the sunlight term is down by a factor of 50 or greater at wavelengths longer than  $3.6 \mu\text{m}$ . Alternately, the flights can be scheduled when the sun is not visible.

If the instrument flight altitude is limited to a value such that the atmosphere can be considered to be single layer having uniform average temperature and pollutant concentration the source expression is further simplified to

$$E(\lambda) = [\epsilon_G(\lambda)N_G^0(T_G, \lambda) - N_{ATM}^0(T_{ATM}, \lambda)]\tau_{ATM}(\lambda) + N_{ATM}^0(T_{ATM}, \lambda) .$$

The last term here is not a function of atmospheric (pollutant) transmission and so creates a spurious output. This spurious output is slightly sensitive to atmospheric temperature and can be removed by zero adjustment of the instrument.

The equation  $\text{SNR} = P/dP$  can now be expanded:

$$P = [\epsilon_G N_G^0(\lambda, T) - N_{ATM}^0(\lambda, T)]\Delta\lambda A_o \Omega_o \eta_o M$$

$$dP = NEP/\eta_e = (A_d/4t_c)^{\frac{1}{2}} / (\eta_e D^*)$$

and

$\epsilon_G$  = Terrain emissivity. See Table 7.3.10-1 and Figure 7.3.10-5.

Units: none

$N_G^0$ ,  $N_{ATM}^0$  = Terrain and atmosphere, respectively; black-body spectral radiance. See Figure 7.3.10-4.  
Units: watts/cm<sup>2</sup> micron-steradian

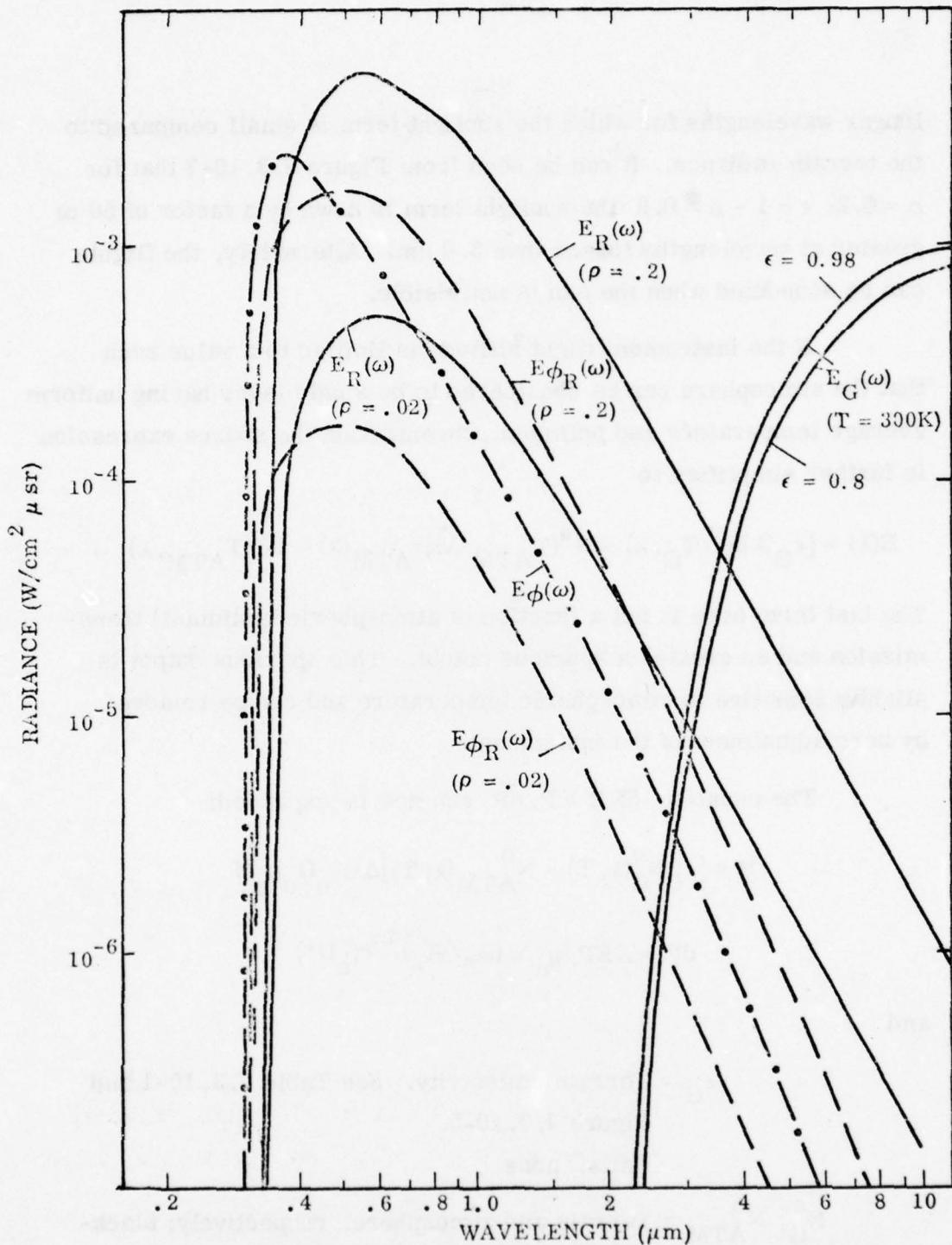


Figure 7.3.10-7. Upwelling Radiation at the Top of the Atmosphere. Contributions from reflected sun radiation  $E_R(\omega)$ , atmospheric  $E_{\phi}(\omega)$  and  $E_{\phi}R(\omega)$ , and thermal radiation  $E_G(\omega)$ . Ground temperature = 300°K, sun zenith angle = 45° (Ref. 270).

$\Delta\lambda$  = Wavelength interval defined by the optical filter.

Units: microns

$A_o$  = Area of entrance optics.

Units: cm<sup>2</sup>

$\Omega_o$  = Solid angle of field of view.

Units: steradians

$A_d$  = Area of detector.

Units: cm<sup>2</sup>

If not known, may be approximated by  $1.59 A_o \Omega_o^*$ .

$\eta_o$  = Optical efficiency. Use 0.1\* unless otherwise known.

Units: none

$t_c$  = System time constant, 0 - 63% response.

Units: seconds

$\eta_e$  = Data processing efficiency. Use 0.3\*unless otherwise known.

Units: none

D\* = Detector specific detectivity. Use value from

Figure 7.3.10-6 unless otherwise known.

Units: cm Hz<sup>1/2</sup>/watt

NEP = Noise-equivalent power.

Units: watts

When quoted in system specification, NEP may

have units of watts/Hz<sup>1/2</sup>; if so, divide given value

by  $\sqrt{4t_c}$  before using.

\*typical values of a well-designed instrument.

$M$  = Modulation factor. Exact calculation requires knowledge of molecular spectral band fine structure parameters. For low concentrations assume:

$$M \approx KcR$$

where  $K$  = Empirically determined constant. Unless otherwise known, use 1.0 or  $0.1/R_c$ ; whichever is smaller.

Units:  $\text{cm}^{-1}$

$c$  = Fractional concentration of pollutant in atmosphere being monitored, i.e.,  $\text{ppm} \times 10^{-6}$ .

$R$  = Optical path length in atmosphere being monitored.

Units: cm

#### Calculation Procedure:

Because  $c$  (concentration),  $R$  (range) and  $t$  (time constant) are often field variables, it is convenient to calculate  $\text{SNR} = (\text{constant}) \times (cR\sqrt{t})$  so that the comparative effect of these variables on SNR is easily determined.

$$\text{SNR} = G(cR\sqrt{t})$$

where:

$$G = 2(\epsilon_G N_G^0 - N_{ATM}^0) \Delta\lambda A_o \Omega_o \eta_o \eta_e D^* K / \sqrt{A_d}$$

$A_o$  = Area of entrance optics,  $\text{cm}^2$

$\Omega_o$  = Solid angle of field of view; approximately  $(d/R)^2$ ,  
 where  $d$  = width of field of view from  $R$  altitude.  
 For example, if 50 meter ( $= d$ ) field of view at  
 1000 meters ( $= R$ ) altitude,  $\Omega_o = 0.0025$  steradians.  
 If the field of view is expressed as an angle,  $B$ ,  
 the formula is  $\pi \sin^2(B/2)$ ; e.g., if  $B = 5^\circ$ ,  
 $\Omega_o = 0.006$  steradians.

If actual values are not known for the remaining variables the following values may be assumed:

$\epsilon_G$ : assume Table 7.3.10-1, Figure 7.3.10-5, or 0.8

$N_G^0$ : assume Figure 7.3.10-4 using  $20^\circ\text{C}$

$N_{ATM}^0$ : assume Figure 7.3.10-4 and from  $20^\circ\text{C}$   
 subtract  $3^\circ$  for each 1000 meters flight altitude

$\Delta\lambda$ : assume 0.1

$A_d$ : assume  $1.59 A_o \Omega_o$

$\eta_o$ : assume 0.1

$\eta_e$ : assume 0.3

$D^*$ : assume Figure 7.3.10-6

$k$ : assume 1.0 or  $0.1/RC$ , whichever is smaller

Known values are always to be preferred over these typical values.

#### Analytical Determination of SNR

Step 1: Calculate  $G$  from above formula using known or assumed parameter values.

Step 2: To calculate SNR given  $c$ ,  $R$ ,  $t$ :

$$\text{SNR} = G c R \sqrt{t}$$

Step 3:To calculate  $c$  given SNR,  $R$ ,  $\tau$ :

$$c(\text{ppm} \times 10^{-6}) = \text{SNR}/G R\sqrt{\tau}$$

Graphical Determination of SNR

The formula  $\text{SNR} = G(cR\sqrt{\tau})$  can be written  $\text{SNR} = (F)(U)(V)(cR\sqrt{\tau})$   
for which

$$F = (\epsilon_G N_G - N_{\text{ATM}}) \Delta\lambda$$

$$\begin{aligned} U &= (A_o \Omega_o / \sqrt{A_d}) \\ &= 2\eta_o \eta_e D^* K \end{aligned}$$

Step 1:Calculate:  $F$ 

$$\text{Assume: } \epsilon_G = 1.0$$

$$\Delta\lambda = 0.1 \mu\text{m}$$

Flight altitude = 1000 m, 2000 m, 3000 m

Known ground temperature

Known altitude of inversion layer

Known wavelength

Result: Plots in Figures 7.3.10-8a through 7.3.10-8h give  $F$  as a function of ground temperature and flight altitude. Do not choose an altitude higher than the inversion layer.

Curve (a)	Wavelength = 3 $\mu\text{m}$
(b)	Wavelength = 4 $\mu\text{m}$
(c)	Wavelength = 5 $\mu\text{m}$
(d)	Wavelength = 6 $\mu\text{m}$
(e)	Wavelength = 7 $\mu\text{m}$
(f)	Wavelength = 8 $\mu\text{m}$
(g)	Wavelength = 9 $\mu\text{m}$
(h)	Wavelength = 10 $\mu\text{m}$

7.3. 10. 4i

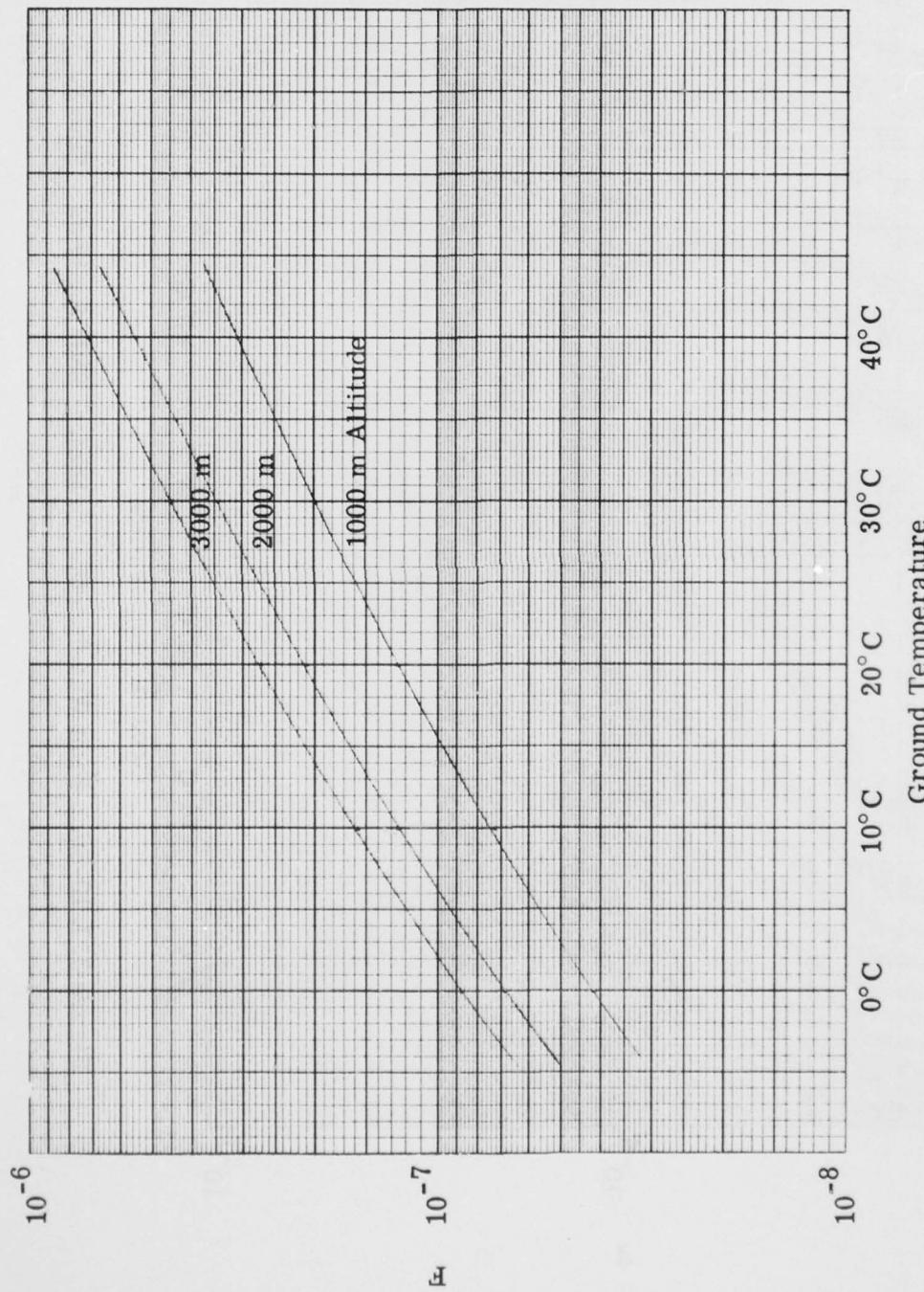


Figure 7.3. 10-8a.  $3 \mu\text{m}$  Wavelength. Graphical SNR Analysis - Step 1.

7.3.10.4j

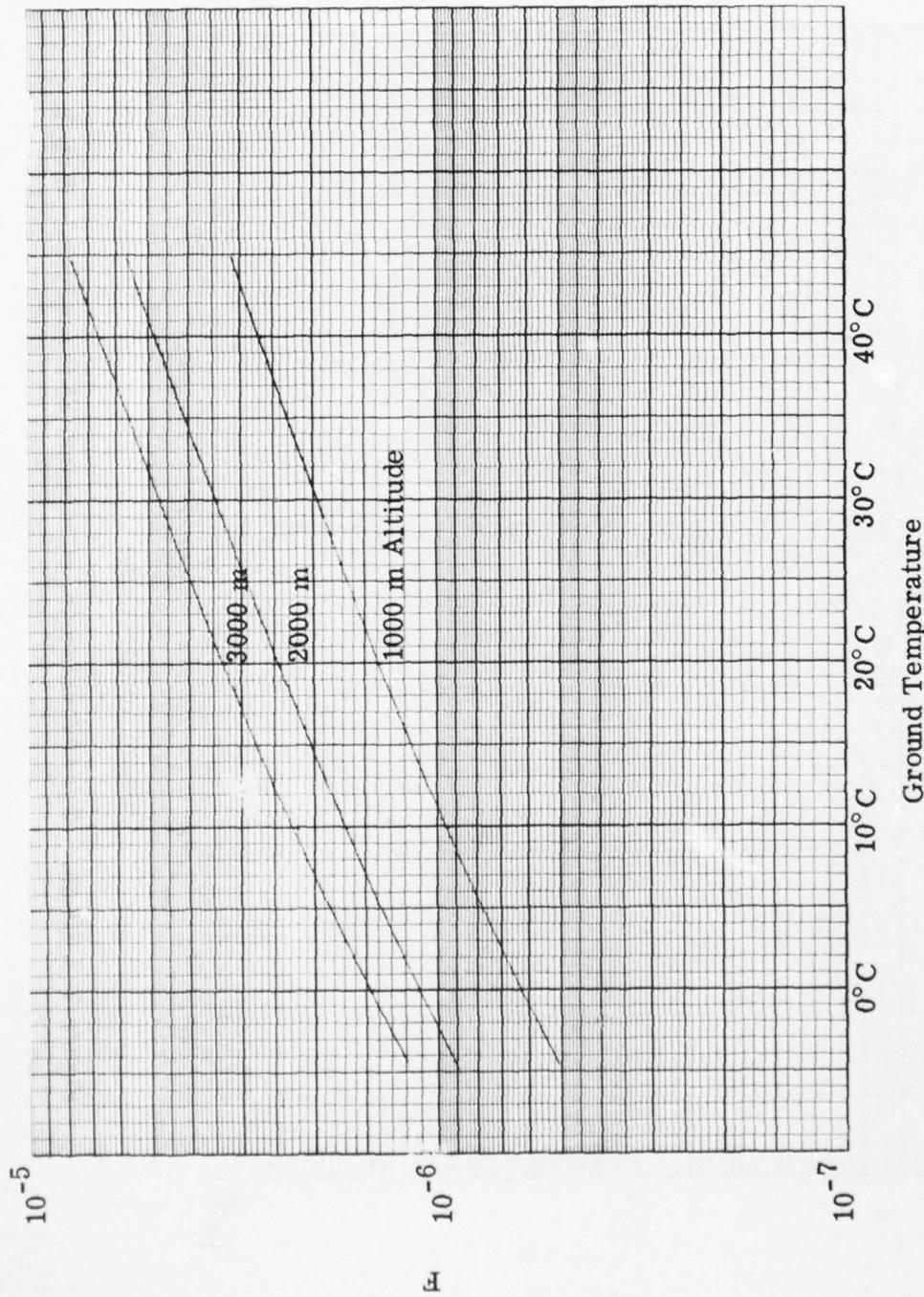


Figure 3.7.10-8b.  $4 \mu\text{m}$  Wavelength. Graphical SNR Analysis - Step 1.

7.3.10.4k

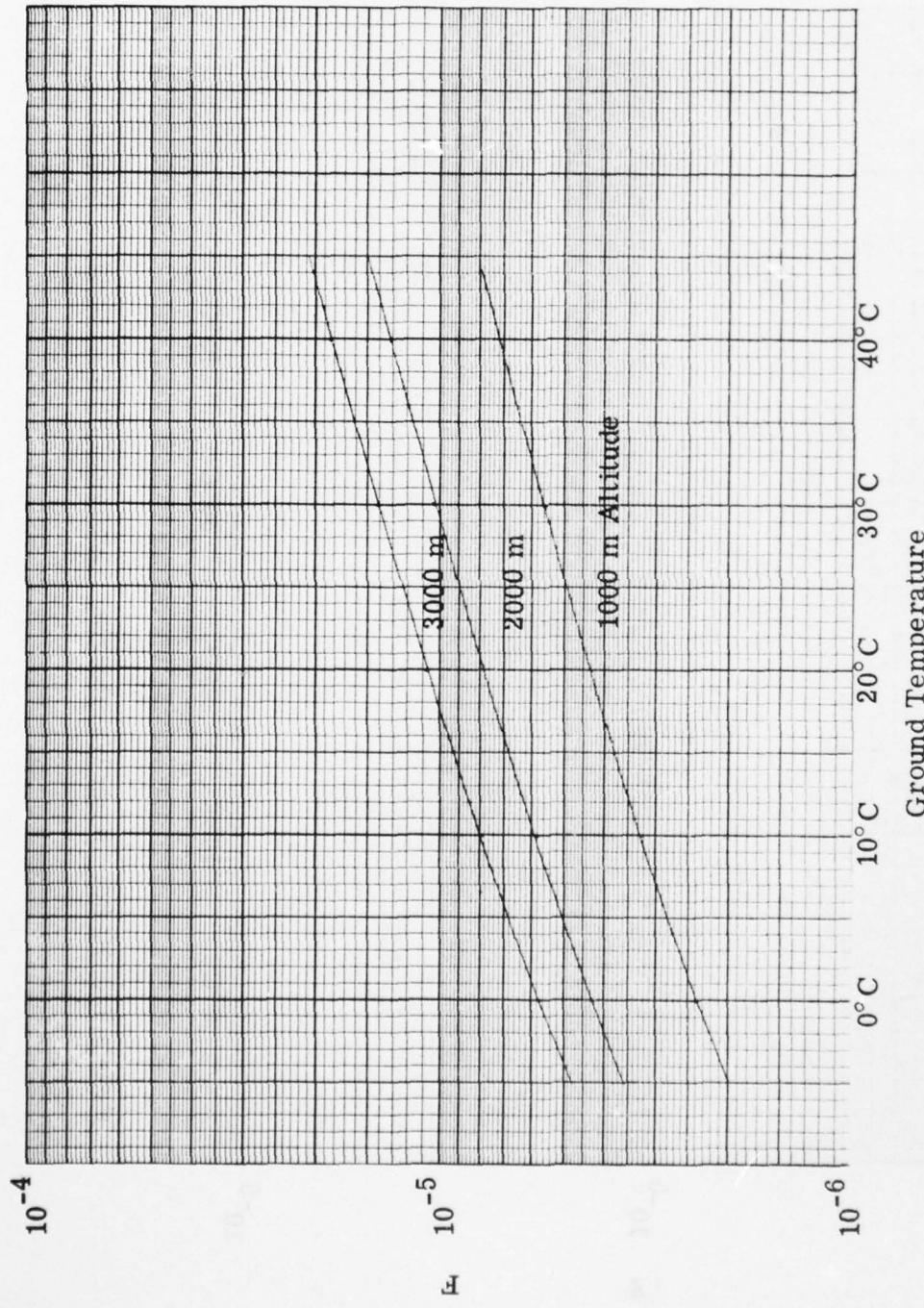


Figure 7.3.10-8c. 5  $\mu\text{m}$  Wavelength. Graphical SNR Analysis - Step 1.

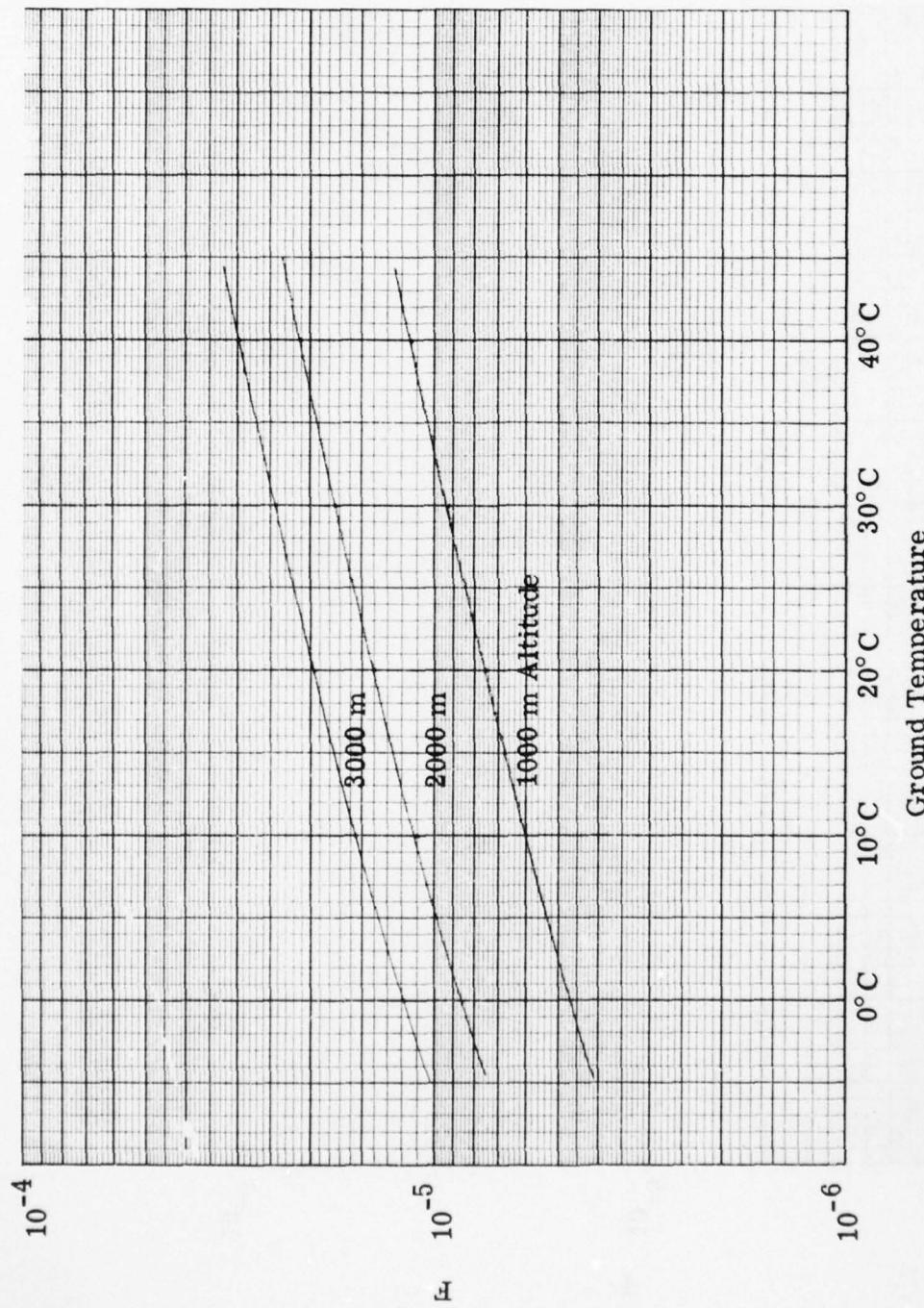


Figure 7.3.10-8d.  $6 \mu\text{m}$  Wavelength. Graphical SNR Analysis - Step 1.

7.3.10.4m

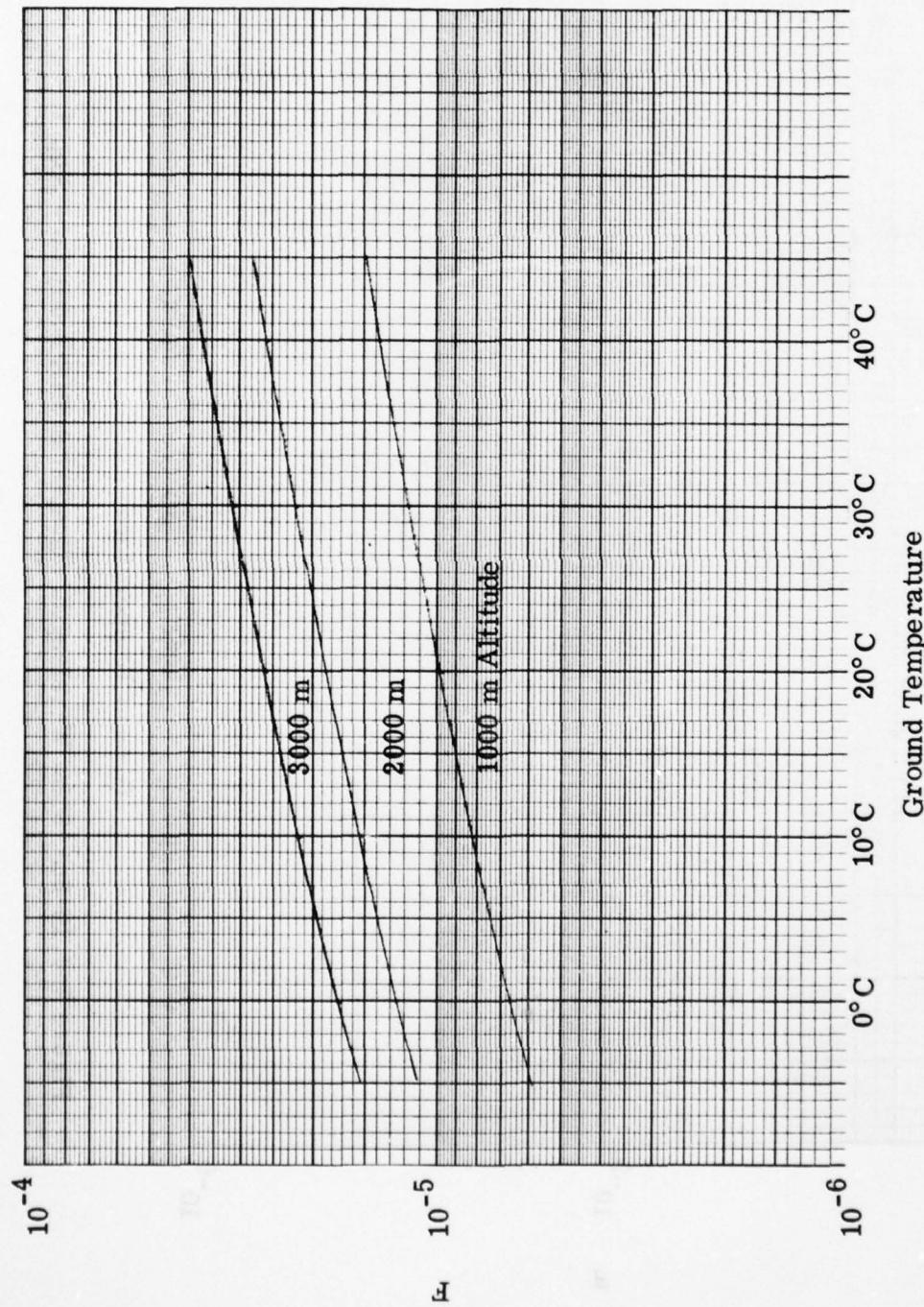


Figure 7.3.10-8e.  $7\mu\text{m}$  Wavelength. Graphical SNR Analysis - Step 1.

7.3.10.4n

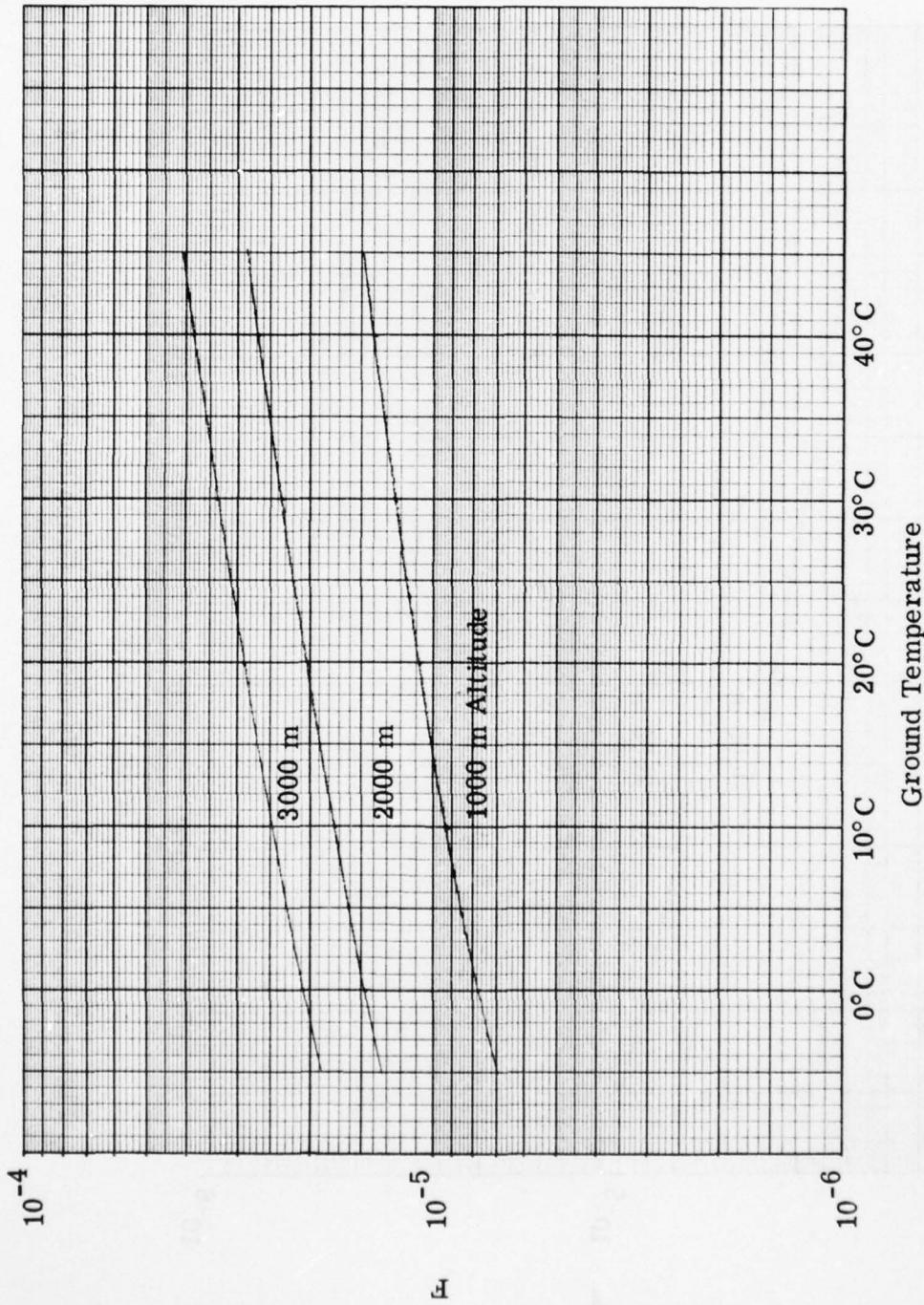


Figure 7.3.10-8f.  $8 \mu\text{m}$  Wavelength. Graphical SNR Analysis - Step 1.

7.3.10.4o

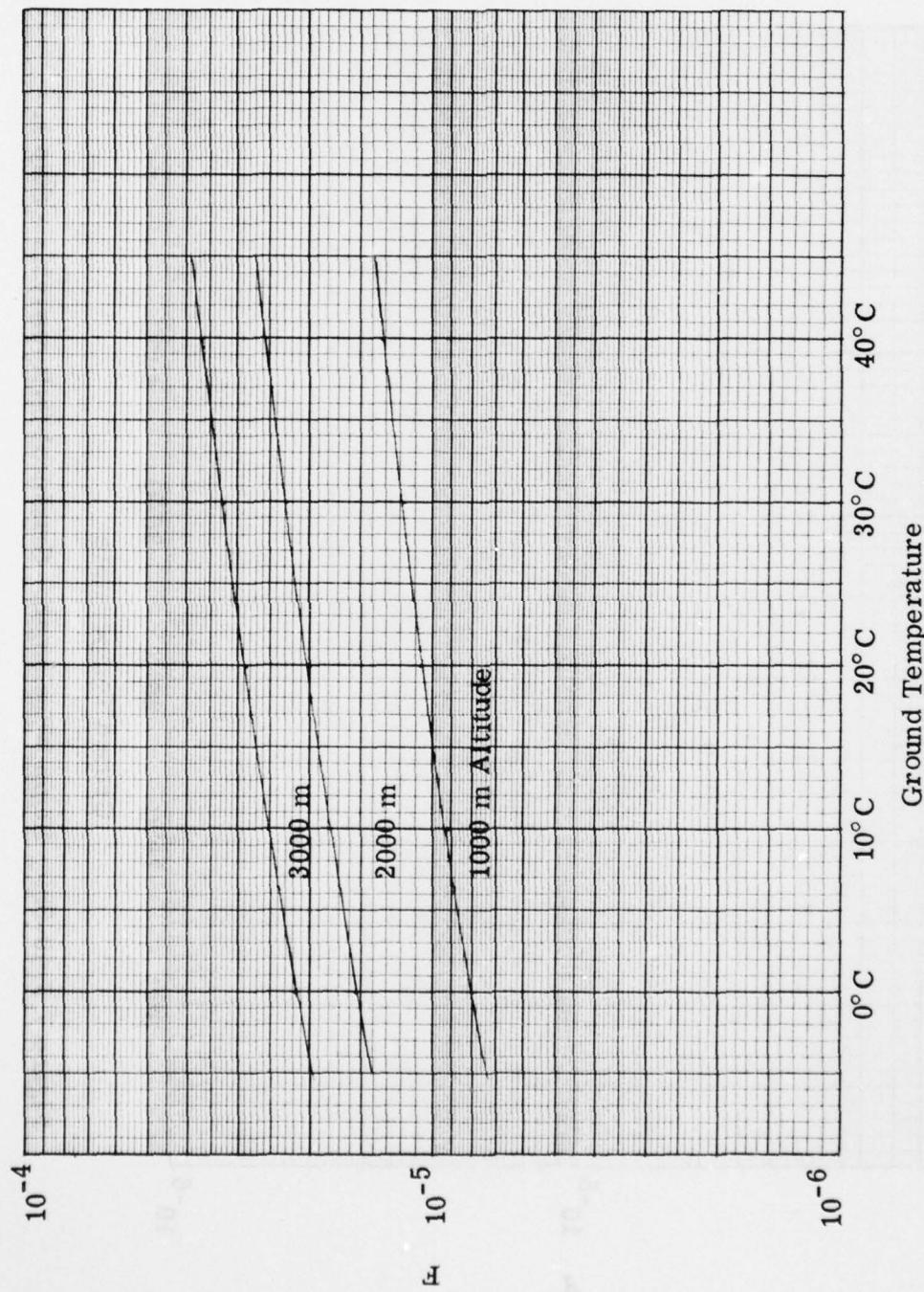


Figure 7.3.10-8g.  $9 \mu\text{m}$  Wavelength. Graphical SNR Analysis - Step 1.

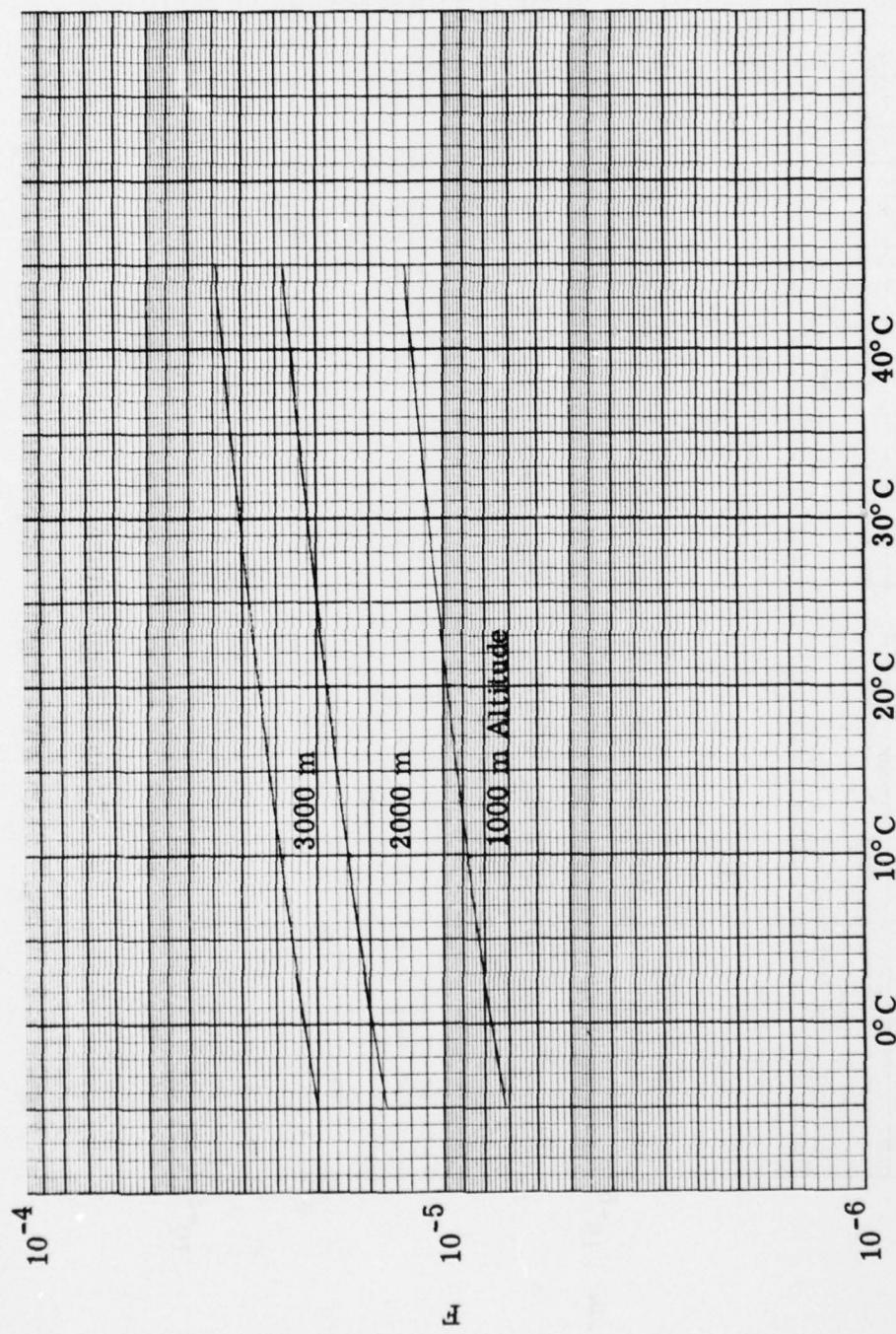


Figure 7.3.10-8h.  $10\ \mu\text{m}$  Wavelength. Graphical SNR Analysis - Step 1.

Step 2:

Calculate:  $(F)(R)$

Assume: Value of  $F$  from Figure 7.3.10-8

$R$  = flight altitude (meters)

Result: Plot in Figure 7.3.10-9 gives  $FR$  as a function of  $F$  and altitude.

Step 3:

Calculate:  $U$

Assume: The instrument design has been

optimized so that  $A_d$  can be approximated as  $1.59 A_o \Omega_o$ .

Known aperture diameter

Known field of view (degrees)

Result: Plots in Figure 7.3.10-10 give  $U$  as a function of aperture and field of view.

Step 4:

Calculate:  $V$

Assume:  $\eta_o = 0.1$

$\eta_e = 0.3$

$K = 1.0$

$D^*$  = from Figure 7.3.10-6

Result: Plot in Figure 7.3.10-11 gives  $V$  as a function of  $D^*$ .

Step 5:

Calculate:  $(FR)(U)(V)$

Assume:  $FR$  from Step 2

$U$  from Step 3

$V$  from Step 4

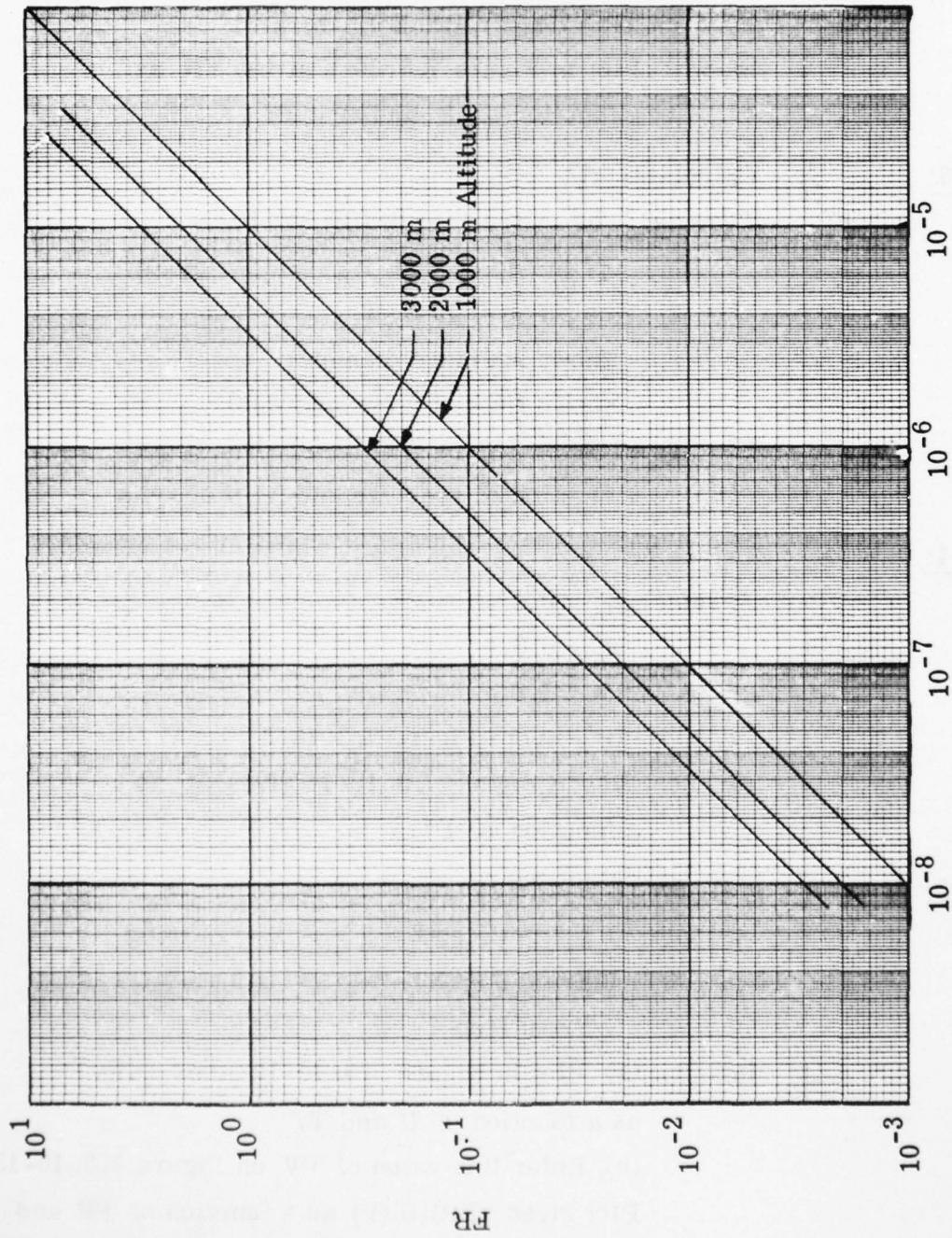
Result: (a) Plot in Figure 7.3.10-12 gives  $(U)(V)$  as a function of  $U$  and  $V$ .

(b) Enter this value of  $UV$  on Figure 7.3.10-13.

Plot gives  $(FR)(U)(V)$  as a function of  $FR$  and  $UV$ .

Values of  $FRUV$  greater than  $10^9$  should not be considered useful due to interference from other species.

7.3.10.4r



F (from Figure 7.3.10-8)

Figure 7.3.10-9. Graphical SNR Analysis - Step 2.

7.3.10.4s

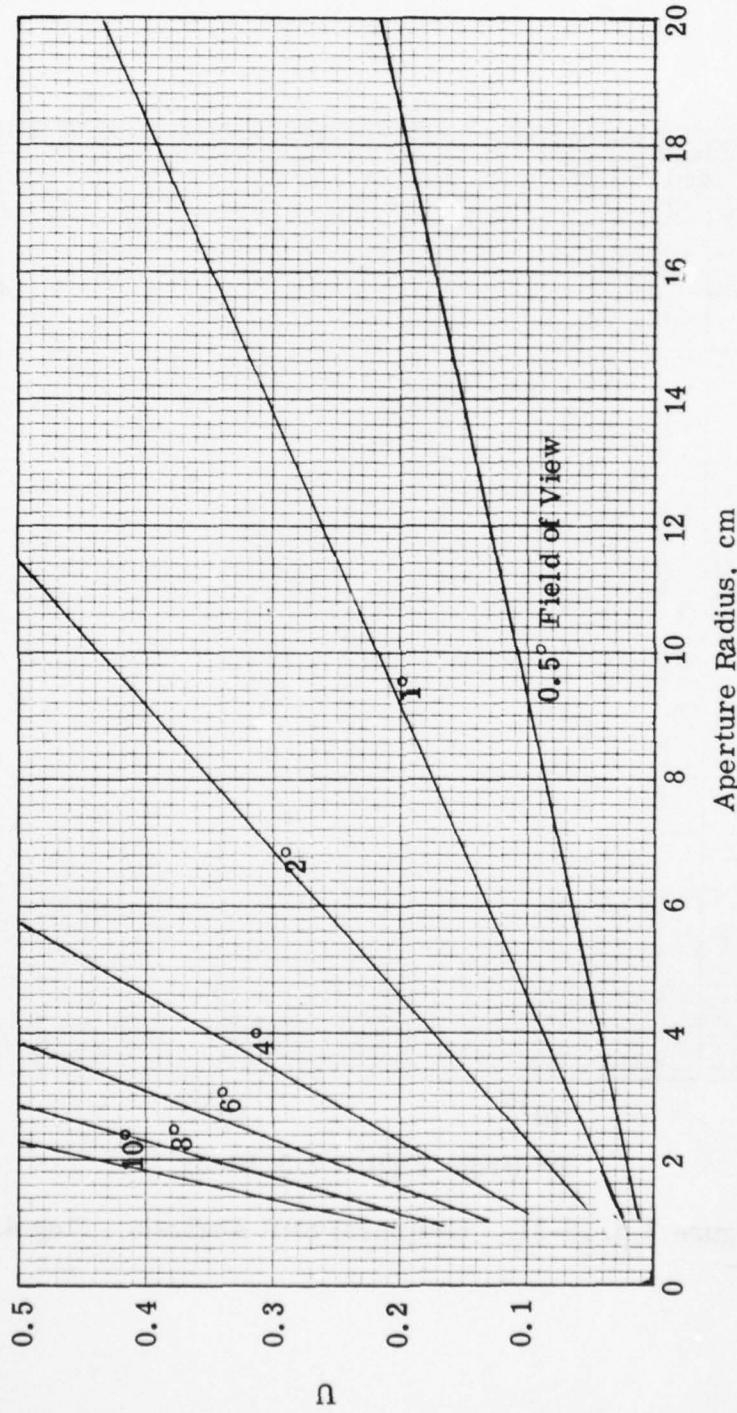


Figure 7.3.10-10. Graphical SNR Analysis - Step 3.

7.3.10.4t

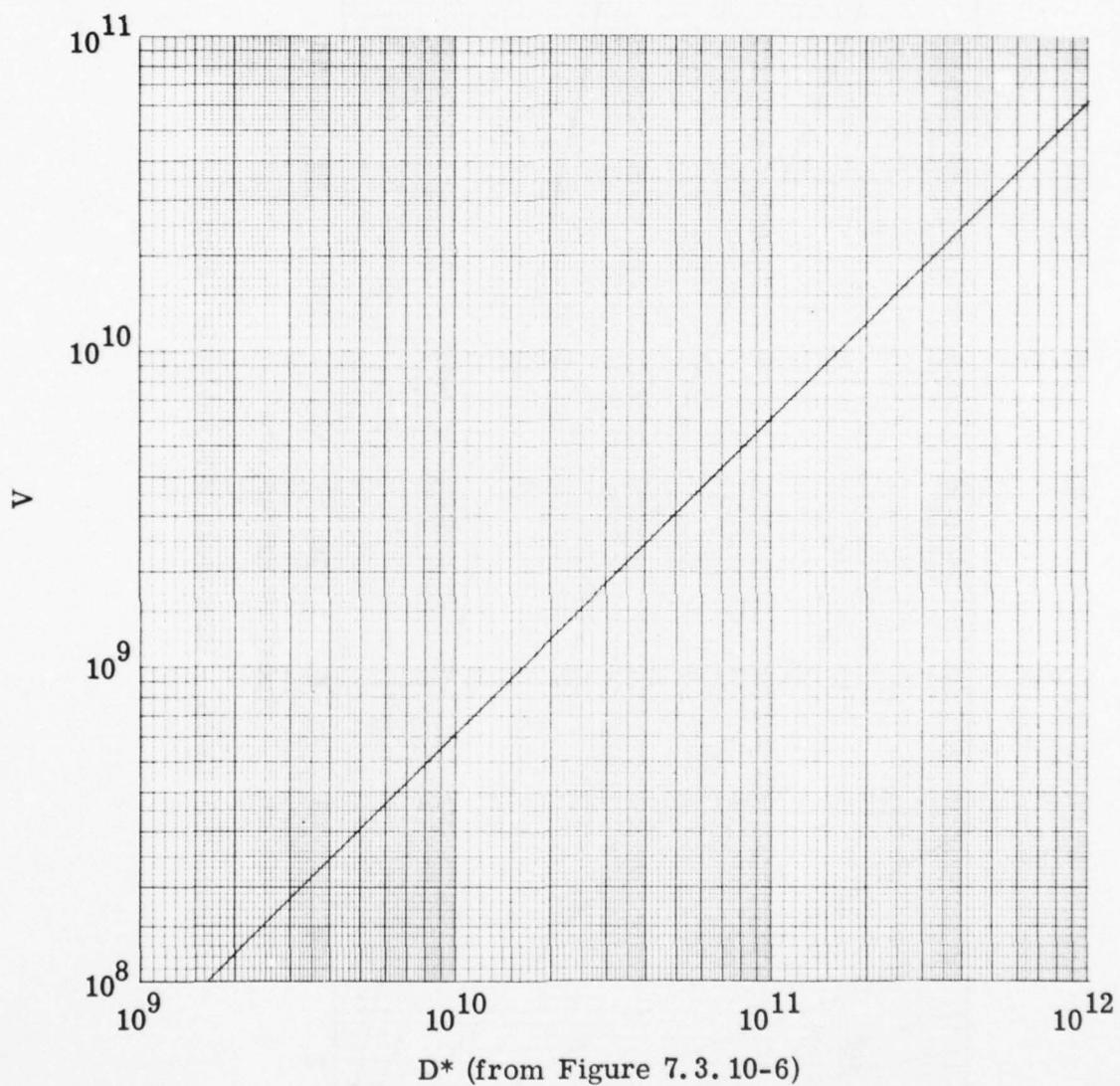


Figure 7.3.10-11. Graphical SNR Analysis - Step 4.

7.3.10.4u

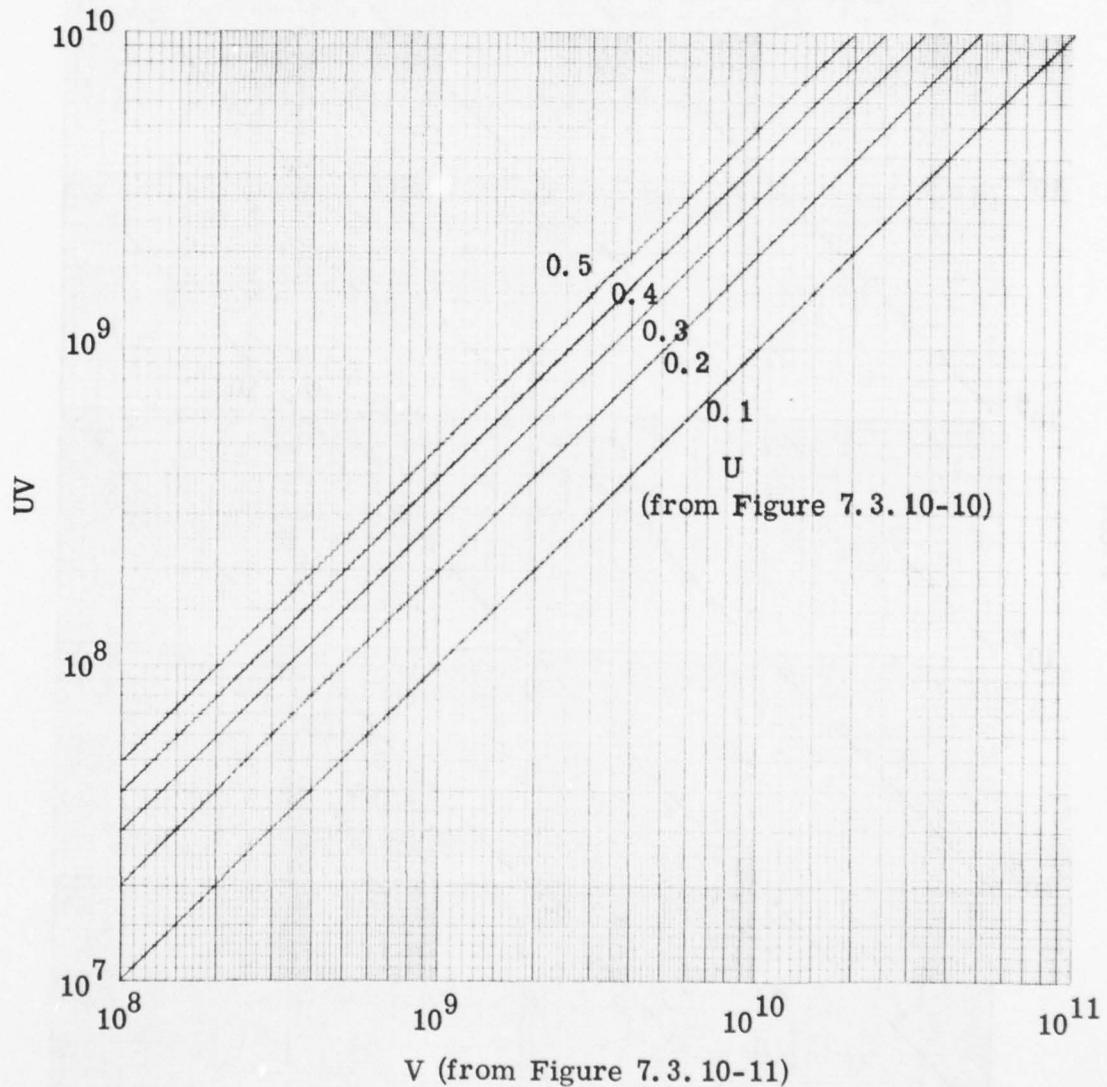


Figure 7.3.10-12. Graphical SNR Analysis - Step 5a.

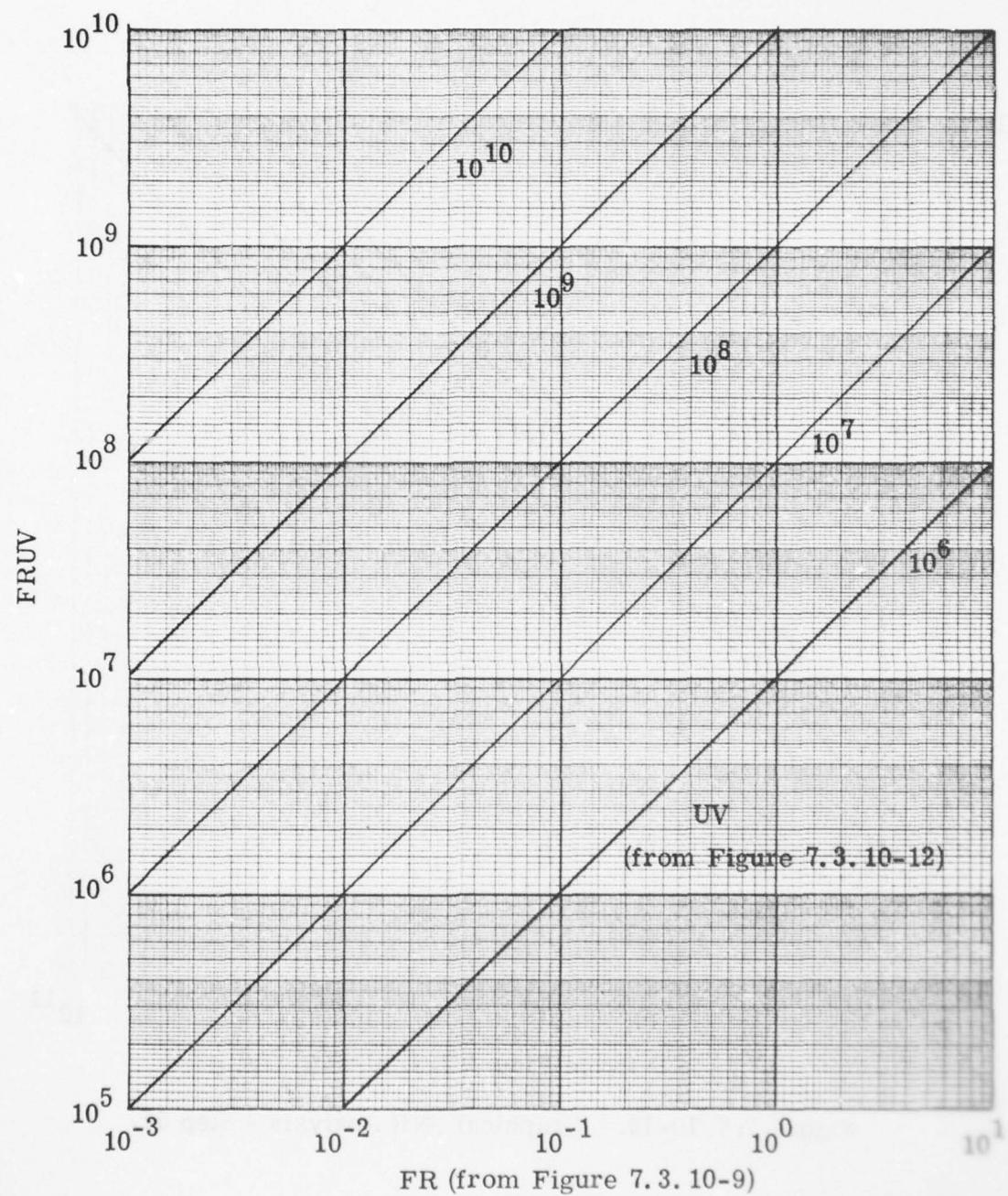


Figure 7.3.10-13. Graphical SNR Analysis - Step 5b.

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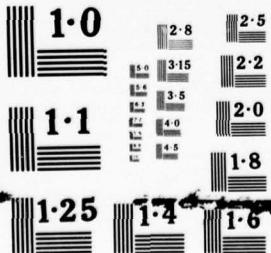
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- Step 6:      Calculate:  $(\text{FRUV})\sqrt{t}$   
                  Assume:  $t$  (time constant) known  
                            (FRUV) from Step 5  
Result: Plot in Figure 7.3.10-14 gives  $(\text{FRUV})\sqrt{t}$   
                                as a function of FRUV and the time constant.
- Step 7:      Calculate:  $\text{SNR} = (\text{FRUV}\sqrt{t})c$   
                  Assume:  $\text{FRUV}\sqrt{t}$  from Step 6  
                            Various values of time constant  
Result: Plots in Figure 7.3.10-15 give resulting  
                            signal-to-noise ratio for various values of  
                            pollutant concentration.

#### 7.3.10.5 Special Performance Requirements

The non-special requirements were discussed in Section 7.1,  
Procedures Applicable to All Remote Sensors.

In addition, the user should be cautioned about proceeding when  
low signal-to-noise ratios are expected, as peak random noise is typically  
a factor of five higher than the rms value commonly quoted.

#### 7.3.10.6 Data Analysis Procedure

Analysis is usually performed by comparing the experimental  
data with an empirically determined calibration curve; theoretical cali-  
bration requires computer analysis of the molecular spectral band fine  
structure parameters.

A calibration curve is obtained experimentally by inserting a  
calibration cell into the optical path (see Figure 7.3.10-1) using a black-  
body background and charging the cell with known concentrations of the  
pollutant gas. The temperatures of the gas (representing the atmosphere)  
and the blackbody background (representing the earth) are recorded and  
converted to units of radiance.

7.3.10.6b

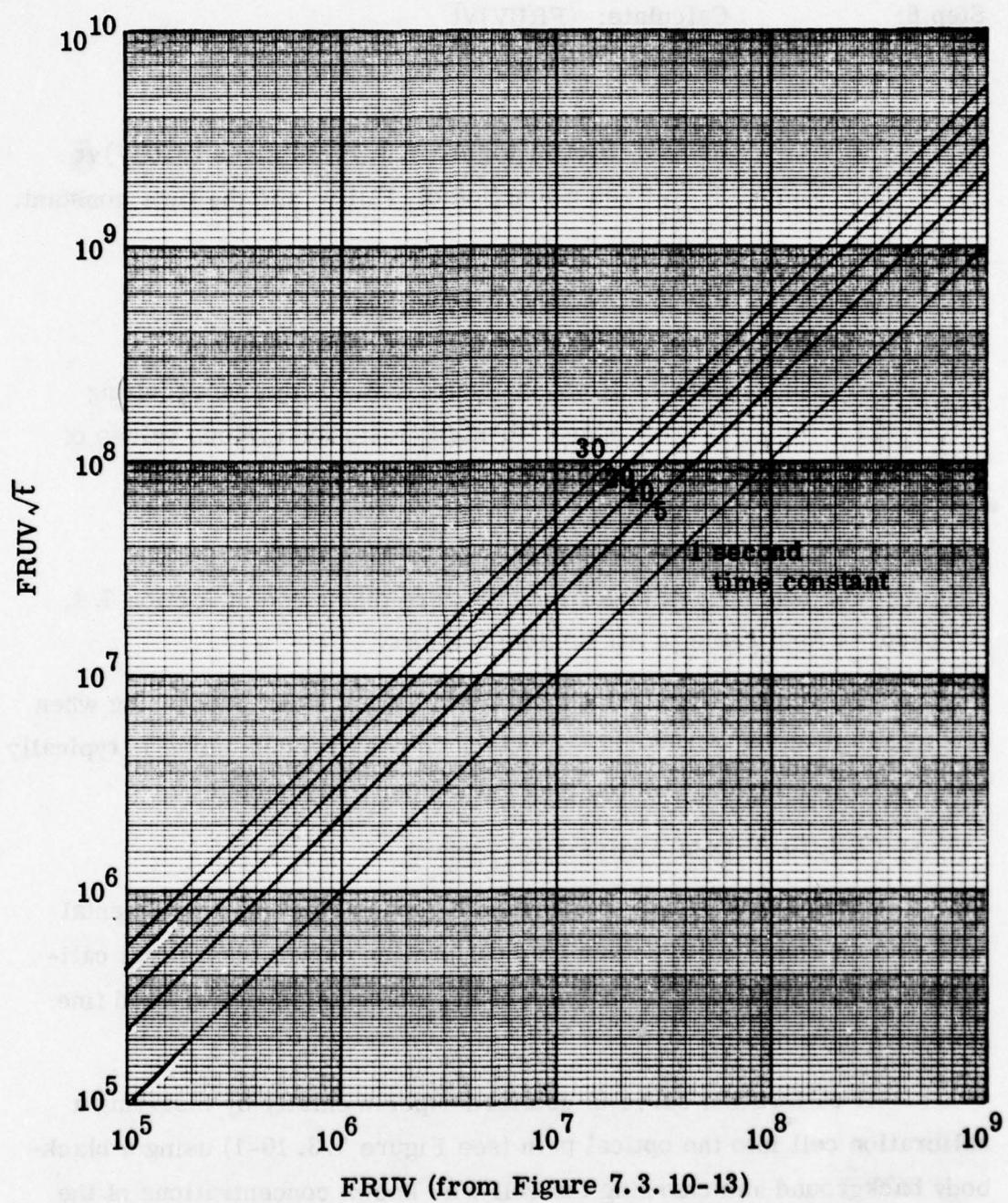


Figure 7.3.10-14. Graphical SNR Analysis - Step 6.

7.3. 10.6c

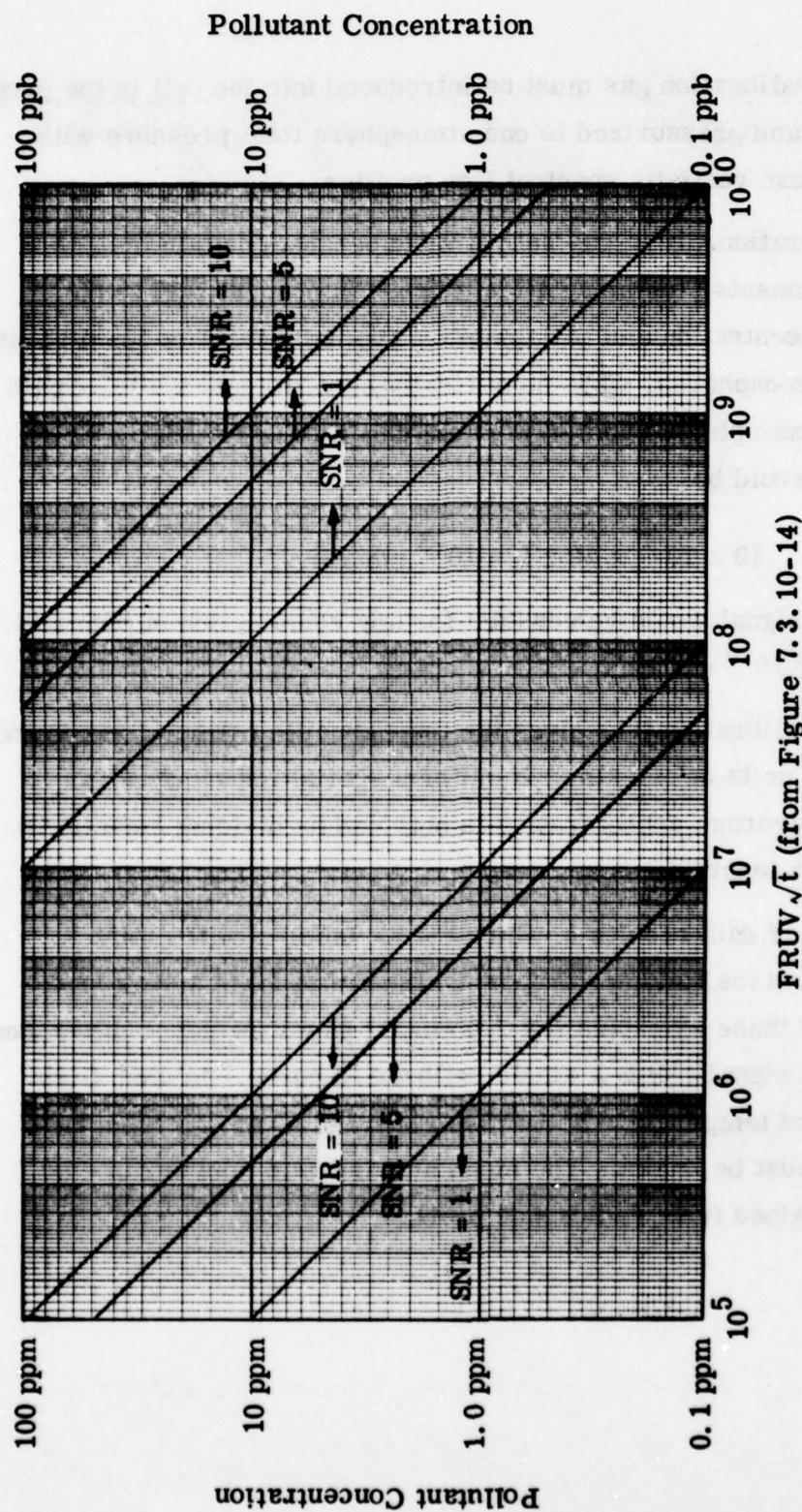


Figure 7.3.10-15. Graphical SNR Analysis - Step 7.

The calibration gas must be introduced into the cell in the proper concentration and pressurized to one atmosphere total pressure with nitrogen to cause realistic spectral line profiles.

Calibration with a gas cell is valid because, within the limits of these instruments, the modulation (signal) is proportional to the product of concentration and path length. The units for this quantity are centimeter-atmospheres. It is numerically equal to ppm  $\times 10^{-6} \times$  path length. For example, 10 ppm in a 50 cm cell through which the beam passes twice would be

$$10 \times 10^{-6} \times 50 \times 2 = 10^{-3} \text{ cm atm}$$

The resulting signal would be constant for any combination of ppm and range equaling  $10^{-3}$  cm atm.

The calibration thus gives the total specific pollutant gas in the optical path in units of cm-atm. If uniform spatial distribution is assumed, the average concentration is obtained by dividing cm-atm by the optical path length.

A set of data results in which the variables are the total pollutant gas and the radiance difference the atmosphere and ground. The product of these variables (total pollutant gas  $\times$  radiance difference) plotted against signal yields a single calibration curve. In use, flight altitude, ground temperature and emissivity, and mean atmospheric temperature must be known. The mean atmospheric temperature is preferably obtained from radiosonde probe.

#### 7.4 Remote Monitors Providing Line Integral Data

In Section 6.2.2.2, Selection and Ranking, none of the Line Integral Monitors was judged sufficiently developed to be ranked acceptable at this time for Air Enforcement Monitoring. However, the two uplooking monitors presented here, especially the one using a gas filter correlation receiver, are very promising for future selection. An uplooking monitor, mounted in a truck or van driven around the airport boundary will measure the vertical burden in a closed loop. From the data together with wind velocity and path geometry, the pollutant mass emission rate may be determined for the entire airport as a source.

Note: Since these monitors are developmental, the Performance Predictions and Data Analysis Procedures are necessarily brief and are not presented in the detail provided for previous instruments.

##### 7.4.1 Infrared Spectrometer (Tunable Receiver) Uplooking Monitor

###### 7.4.1.1 Principle of Operation

An upward looking spectrometer may be used as a passive device to measure the vertical burden (ppm-m) of a pollutant in the infrared, (4 - 10  $\mu\text{m}$ ), if its sensitivity and spectral resolution is sufficient to "isolate" the spectral radiance emitted by the pollutant from that emitted by other atmospheric species. Any pollutants in this spectral region for which sensitivity and resolution requirements are met may be monitored; which meet these criteria are not yet determined. The radiance is measured at two adjacent wavelengths, one for the pollutant emission, and one for the clean atmosphere emission. The difference of these radiances, together with knowledge of the atmospheric temperature, is used to estimate the vertical burden of the pollutant.

#### 7.4.1.2 System Description

The system consists typically of a collecting telescope, a spectrometer, including a moveable grating to vary the wavelength of the radiation leaving the exit slit, and a detector system. A calibration source may be built into the spectrometer, or it may be externally viewed by the telescope. A schematic of a scanning spectrometer system is shown in Figure 7.4.1-1.

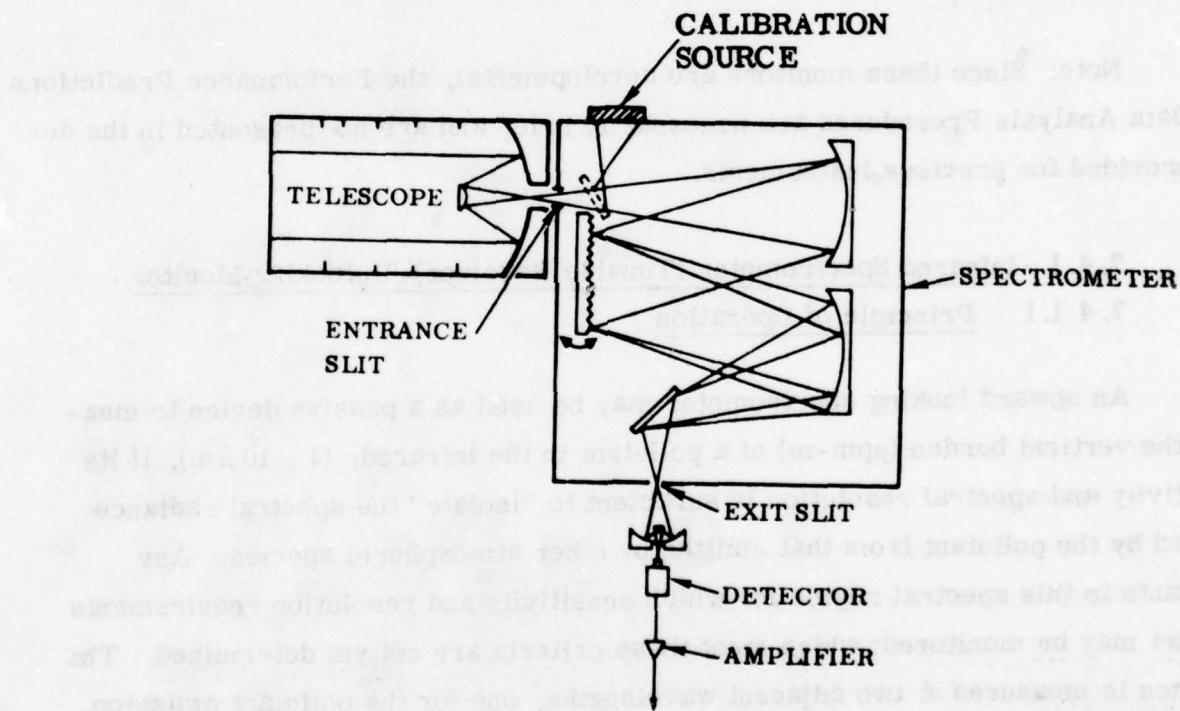


Figure 7.4.1-1. Schematic of a Scanning Spectrometer

### 7.4.1.3

#### 7.4.1.3 System Parameters

##### Availability

No tunable receivers appear to be currently used in the passive upward mode, although General Dynamics Convair<sup>(271)</sup> developed a scanning spectrometer system some years ago.

##### Operational Wavelength Region

Window regions in 4 - 10  $\mu\text{m}$ .

##### Detector

Commercially available detectors with highest  $D^*$  at 77K are 4  $\mu\text{m}$  Indium Antimonide, 77K,  $D^* \sim 5 \times 10^{10} \text{ cm Hz}^{1/2} \text{ w}^{-1}$ , size 0.1 to 3 mm diameter.

10  $\mu\text{m}$  Lead Tin Tellutide, 77K,  $D^* \sim 5 \times 10^{10} \text{ cm Hz}^{1/2} \text{ w}^{-1}$ , size 0.05 to 2 mm square.

##### Optics

Collecting Aperture	$A_o$
Solid Angle	$\Omega_o$
Optical Efficiency	$\eta$
Detector Optics	$A_d \Omega_d (= A_o \Omega_o)$

These parameters are variables which must be chosen to fulfill the operational requirements.

##### Electronic Bandpass

$$\Delta f = \frac{1}{4t_c}$$

where  $t_c$  is the integration time.

### 7. 4. 1. 4 a

#### 7. 4. 1. 4 Theoretical Performance Prediction

Based on the selected system parameter, the performance can be predicted for a detector-noise-limited system. The signal to noise ratio for the system is given by

$$\begin{aligned} \text{SNR} &= \frac{\eta A_o \Omega_o \Delta\lambda [N_{\lambda_1} - N_{\lambda_2}]}{\sqrt{2} \text{ NEP}} \\ &= \eta \sqrt{\frac{A_o \Omega_o}{2 \Delta f}} \frac{D^* \Delta\lambda [N_{\lambda_1} - N_{\lambda_2}]}{\text{f/no}} \end{aligned}$$

where  $f/\text{no} \approx (\Omega_d)^{-1/2}$ ,  $\Omega_o \approx 0.17 \Delta\lambda/\lambda$  for spectrometers,  $N_{\lambda_1}$  is the radiance at the wavelength where a pollutant line is located and  $N_{\lambda_2}$  is the radiance between absorption lines.

This may be re-written as

$$\text{SNR} = \eta \left( \frac{A_o \Omega_o}{2 \Delta f} \right)^{1/2} \frac{D^* \Delta\lambda \tau_c \epsilon_p N^0(\lambda, T)}{\text{f/no}}$$

where  $\tau_c$  is transmissivity of "clean" atmosphere,  $\epsilon_p$  is the emissivity of the pollutant layer, and  $N^0(\lambda, T)$  is the atmospheric blackbody radiance.

Thus the SNR of a given instrument depends on the state of the atmosphere, i. e., the amount of water vapor and aerosol (these determine  $\tau_c$ ), and the atmospheric temperature, and the amount of pollutant.

7. 4. 1. 4b

To compute SNR:

Step 1. From instrument parameters calculate the parameter (IP)

$$(IP) = \eta \left( \frac{A_o \Omega_o}{2\Delta f} \right)^{1/2} \frac{D^* \Delta \lambda}{f/no}$$

Typical values might be

$$\eta = 0.01$$

$$A_o = 78.5 \text{ cm}^2$$

$$\Omega_o = 6.8 \times 10^{-5} \text{ sr}$$

$$\Delta f = 4.17 \times 10^{-3} \text{ Hz (60 sec time constant)}$$

$$D^* = 5 \times 10^{10} \text{ W}^{-1} \text{ Hz}^{1/2} \text{ cm}$$

$$\Delta \lambda = 0.005 \mu\text{m}$$

$$f/no = 5$$

$$\text{Hence } (IP) = 4.00 \times 10^5 \text{ for this example.}$$

Step 2: Determine the atmospheric transmission  $\tau_c$ . This should be performed by computer program, if available, using known or assumed values of the atmospheric structure parameters. This will probably not be possible, and the typical value

$$\tau_c = 0.9$$

may be assumed.

Step 3: Measure or estimate atmospheric temperature. Determine  $N^0$  from Figure 7.4.1-4.

### 7.4.1.4c

Step 4: Calculate  $\epsilon_p$  for pollutant thickness (ppm-m). 1 - physical thickness of pollutant layer.

$$\begin{aligned}\epsilon_p &= 1 - e^{-kC_t l} \\ &= 1 - e^{-k(\text{cm}^{-1}\text{atm}^{-1})C_p l (\text{ppm-m}) \times 10^{-4}}\end{aligned}$$

in which the  $10^{-4}$  factor converts ppm-m to cm-atm. The variation of SNR with  $\epsilon_p$  as a function of T is given in Figure 7.4.1-2 for two wavelengths. The values of SNR may be scaled for different instrument parameters, and different values of  $\tau_c$ .

Example: Assume the instrument parameters are as given in Step 1, and the atmospheric conditions give  $\tau_c = 0.9$  and  $T = 290\text{K}$ . Assume  $\text{SNR} = 10$  is required for minimum sensitivity, then from Figure 7.4.1-2 we find  $\epsilon_p \approx 0.035$  for  $10 \mu\text{m}$ .

From Step 4:

$$\epsilon_p = 1 - e^{-k(\text{cm}^{-1}\text{atm}^{-1})C_p l (\text{ppm-m}) \times 10^{-4}}$$

Hence, the minimum detectable  $C_p l$  in ppm-m may be calculated for a given k, and assuming the mixing thickness l, the mean layer minimum detectable concentration  $C_p l$  in ppm may be calculated:

$$C_p l = \left( \frac{1}{kl} \right) \ln (1 - \epsilon_p) - \left( \frac{1}{kl} \right) \ln (1 - \epsilon_p)$$

The variation of minimum detectable concentration with the pollutant layer thickness as a function of k, is given in Figure 7.4.1-3 for the two wavelengths.

Because of the complexity of the calculation of the modulation signal, we are restricted here to describing the effects of the instrument parameters on the resulting SNR. Also, we are restricted to the one pollutant for which the calculations have been done ( $\text{SO}_2$ ) and to the atmospheric conditions which were assumed.

For instrument parameters other than those assumed in Step 1, proceed as follows:

Step 5: Calculate the instrument parameter IP using the formula in Step 1 and using actual values instead of assumed values.

Step 6: Calculate

$$k = IP/4.00 \times 10^5$$

Step 7: Recall the preliminary value of SNR obtained in Step 4, multiply this by the value of IP (Step 6). The result is the actual value of SNR.

$$\text{SNR (actual)} = (k) \text{ SNR (preliminary)}$$

#### Graphical Procedure

A graphical procedure is not presented because the computational variables are limited to the above instrument parameters.

Until further computer calculations are published, the atmospheric and pollutant parameters are limited to those presented in Figures 7.4.1-2 and -3.

The reader is cautioned that this is a preliminary analysis of a developmental instrument.

#### 7.4.1.5 Special Performance Requirements

The general requirements applicable to all remote monitors were described in Section 7.1.1. Special requirements applicable to particular pollutants are described in discussions of other monitors in Section 7.

7. 4. 1. 5b

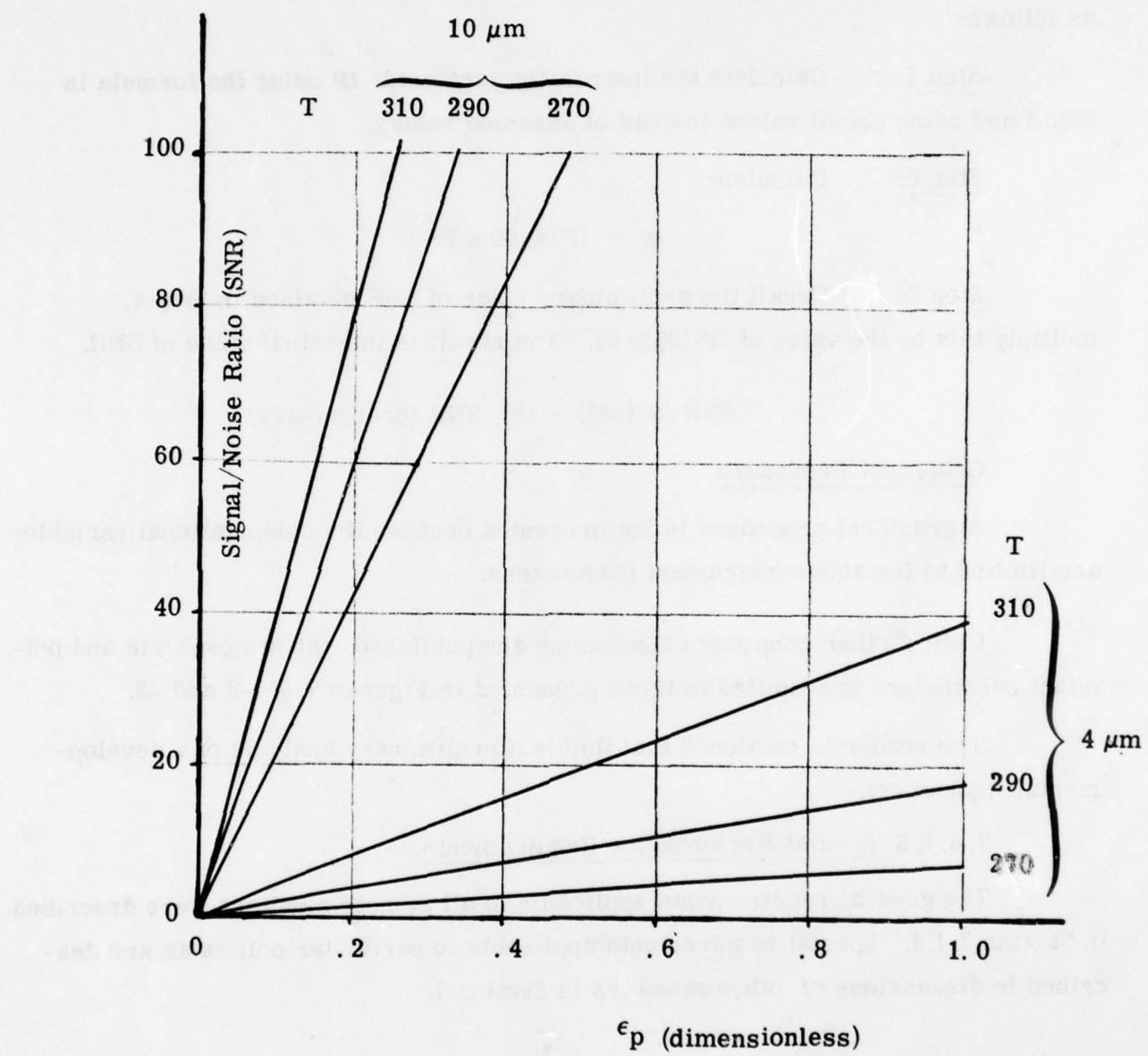


Fig. 7. 4. 1-2

Signal-to-Noise Ratio vs  $\epsilon_p$  for indicated wavelengths and temperatures and Instrument Parameter  $IP = 4 \times 10^5$ .

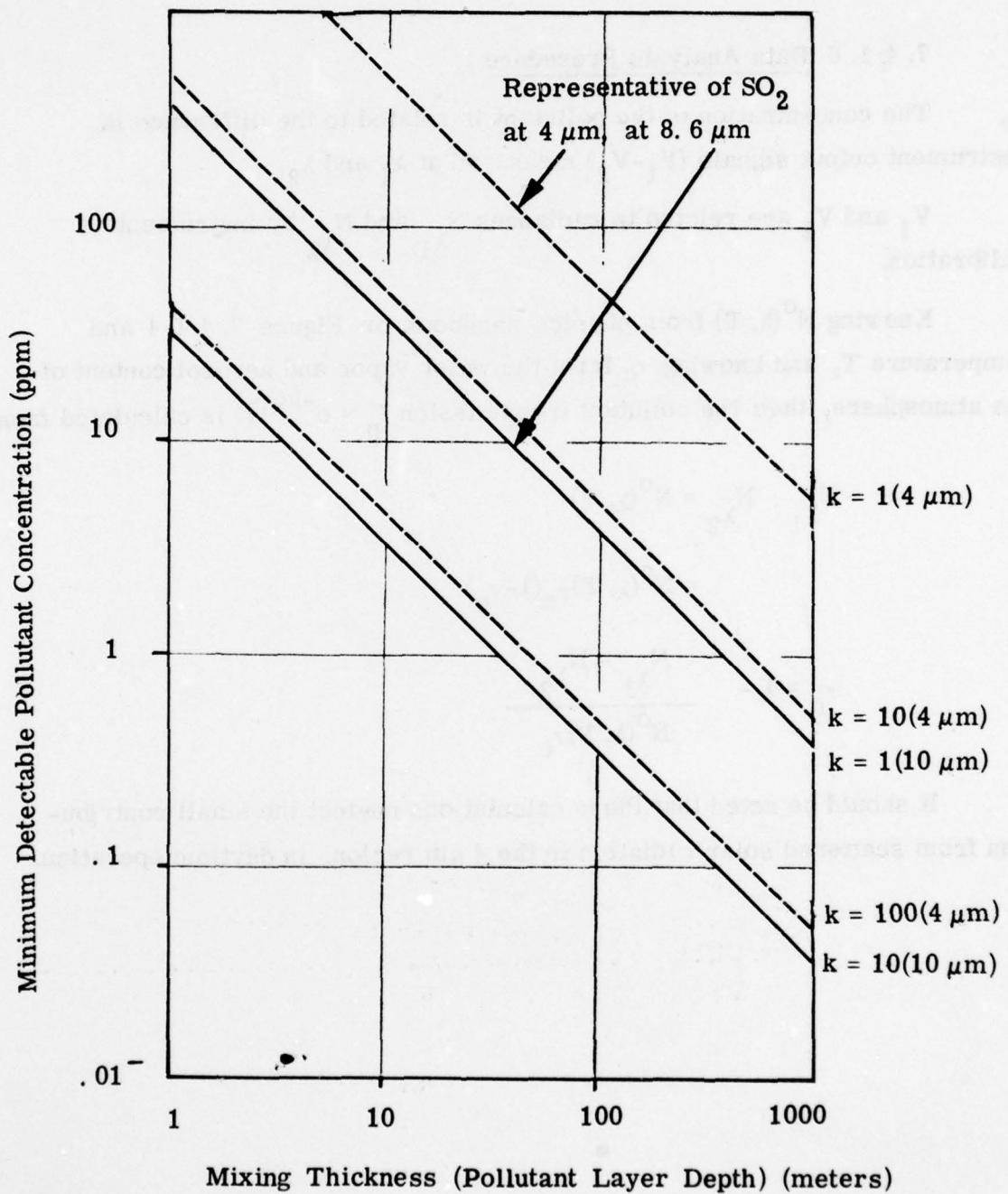


Fig. 7.4.1-3. Minimum pollutant concentration (ppm) vs. mixing depth (meters) for various values of  $k$  (1/cm)

#### 7. 4. 1. 6a

##### 7. 4. 1. 6 Data Analysis Procedure

The concentration of the pollutant is related to the difference in instrument output signals ( $V_1 - V_2$ ) measured at  $\lambda_1$  and  $\lambda_2$ .

$V_1$  and  $V_2$  are related to radiances  $N_{\lambda_1}$  and  $N_{\lambda_2}$  by instrument calibration.

Knowing  $N^0(\lambda, T)$  from physics handbook or Figure 7. 4. 1-4 and temperature  $T$ , and knowing  $\tau_c$  from the water vapor and aerosol content of the atmosphere, then the pollutant transmission  $\tau_p = e^{-kC_p t^1}$  is calculated from:

$$\begin{aligned} N_{\lambda_1} - N_{\lambda_2} &= N^0(\lambda, T) \\ &= N^0(\lambda, T)\tau_c(1 - \tau_p) \end{aligned}$$

$$\tau_p = 1 - \frac{N_{\lambda_1} - N_{\lambda_2}}{N^0(\lambda, T)\tau_c}$$

It should be noted that these calculations neglect the small contribution from scattered solar radiation in the  $4 \mu\text{m}$  region, in daytime operation.

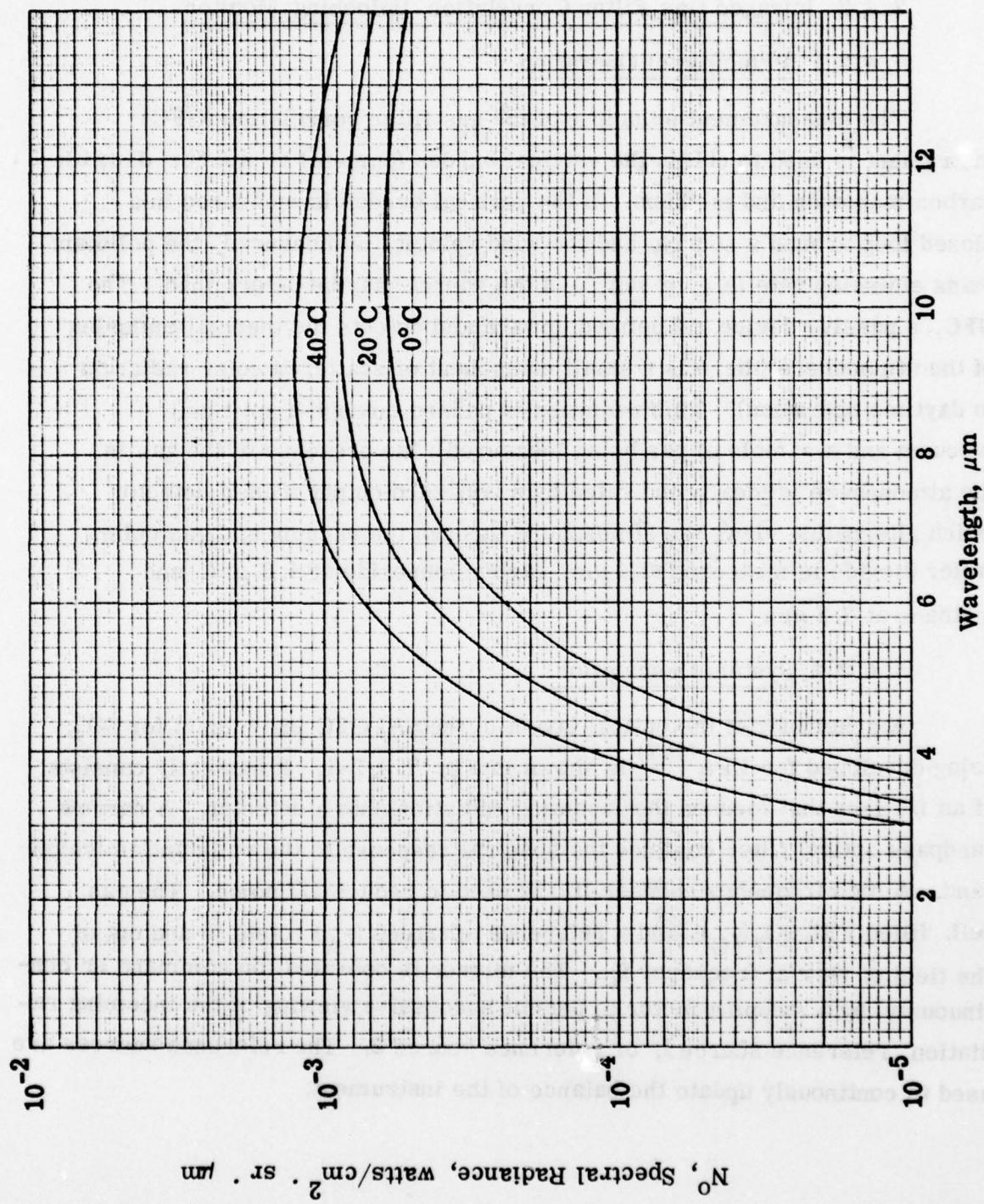


Figure 7. 4. 1-4. Blackbody Source Spectral Radiance.

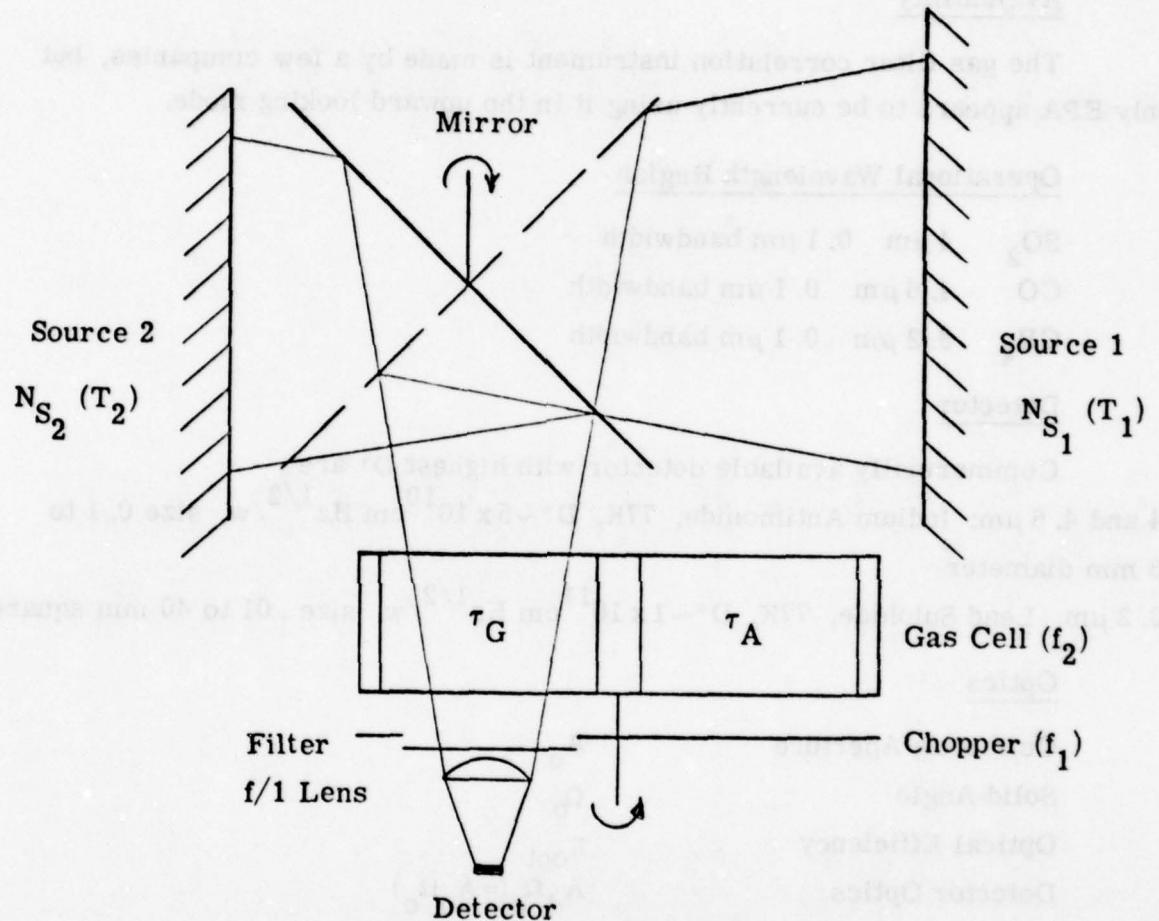
#### 7. 4. 2 Infrared Gas Filter Correlation Uplooking Monitor

##### 7. 4. 2. 1 Principle of Operation

The measurement principle of the gas filter correlation (GFC) instrument is used to obtain the vertical burden (ppm-m) of sulfur dioxide, carbon monoxide and methane. If the vertical burden is measured in a closed loop around a source, and the wind velocity is measured, the pollutant mass emission rate (e.g. g sec<sup>-1</sup>) of the source may be determined. The GFC, a passive device, is pointed upward and detects the thermal emission of the atmosphere (there is a small component of scattered solar radiation in daytime operation). This radiation is passed through a split cell (vacuum and a sample of gas being measured); the presence of the gas in the atmosphere is ideally indicated by a non-zero output from a detector which alternately views the atmosphere through the vacuum and gas cells. Sulfer dioxide is measured at 4  $\mu\text{m}$ , carbon monoxide at 4.6  $\mu\text{m}$ , and methane at 3.2  $\mu\text{m}$ .

##### 7. 4. 2. 2 System Description

A schematic of the optical layout of the SAI GFC instrument for SO<sub>2</sub>, being developed for EPA<sup>(177)</sup> is shown in Fig. 7. 4. 2-1. It basically consists of an f/1 lens that focuses the incoming radiation onto a detector. A narrow bandpass optical filter confines the spectral response to the pollutant emission band. A high frequency chopper ( $f_1$ ) is used to reduce 1/f noise. The gas cell, filled with SO<sub>2</sub>( $\tau_G$ ), and a reference aperture ( $\tau_A$ ) rotate in and out of the field of view at frequency  $f_2$ . The mirror is operated (on command or continuously) by a stepping motor to permit successive viewing of the incoming radiation, reference source 1, or reference source 2. The reference sources are used to continously update the balance of the instrument.



**Figure 7. 4. 2-1. Optical Schematic of Up-Looking Instrument.**

### 7. 4. 2. 3 System Parameters

#### Availability

The gas filter correlation instrument is made by a few companies, but only EPA appears to be currently using it in the upward looking mode.

#### Operational Wavelength Region

$\text{SO}_2$      $4 \mu\text{m}$     $0.1 \mu\text{m}$  bandwidth

$\text{CO}$      $4.6 \mu\text{m}$     $0.1 \mu\text{m}$  bandwidth

$\text{CH}_4$      $3.2 \mu\text{m}$     $0.1 \mu\text{m}$  bandwidth

#### Detector

Commercially available detector with highest  $D^*$  are  
 $4$  and  $4.6 \mu\text{m}$ : Indium Antimonide, 77K,  $D^* \sim 5 \times 10^{10} \text{ cm Hz}^{1/2}/\text{w}$ , size 0.1 to  
3 mm diameter

$3.2 \mu\text{m}$ : Lead Sulphide, 77K,  $D^* \sim 1 \times 10^{11} \text{ cm Hz}^{1/2}/\text{w}$ , size .01 to 40 mm square

#### Optics

Collecting Aperture                       $A_o$

Solid Angle                               $\Omega_o$

Optical Efficiency                       $\eta_{\text{opt}}$

Detector Optics                       $A_d \Omega_d (= A_o \Omega_o)$

These optical parameters are variables which must be chosen to fulfill the operational requirements.

### 7. 4. 2. 4 Theoretical Performance Prediction

The simplified calculations using radiances integrated over narrow spectral bandpasses, as done in Section 7. 4. 1. 4, cannot be utilized here

#### 7. 4. 2. 4b

because the GFC instrument is based on correlation of the rotational structure in a rotation-vibration band. Thus the calculations have to be performed on a line-by-line basis using a large computer.

The signal to noise ratio for a detector-noise-limited GFC system is given by

$$\text{SNR} = \frac{\eta A_o \Omega_o \Delta V D^*}{\sqrt{A_d \Delta f}}$$

where  $\Delta V$  is the GFC signal:

$$\Delta V = N^o(\lambda, T) \Delta \lambda M$$

where  $M$  is the modulation term which depends on the correlation of the rotational spectral structure.

These calculations have been done<sup>(50)</sup> for one pollutant,  $\text{SO}_2$ , at two wavelengths 4 and  $8.6 \mu\text{m}$ . The results of these calculations are given in Fig. 7. 4. 2-1 and may be compared to those for the tunable receiver (Fig. 7. 4. 1-3), showing the superior performance of the GFC. It is seen that the long wavelength region is more sensitive than the short wavelength region, and is also less influenced by the atmospheric temperature. However, the humidity and its distribution through the mixing layer introduce a large uncertainty at the long wavelength region. The following instrument parameters were used in the GFC calculations:

$$\begin{aligned}\eta &= 0.01 \\ A_d &= 0.23 \text{ cm}^2 \\ \Delta f &= 4.17 \times 10^{-3} \text{ Hz (60 sec time constant)} \\ D^*(4\mu\text{m}) &= 3 \times 10^{11} \text{ W}^{-1} \text{ Hz}^{1/2} \text{ cm} \\ D^*(8\mu\text{m}) &= 10^{10} \text{ W}^{-1} \text{ Hz}^{1/2} \text{ cm} \\ A_o \Omega_o &= 0.143 \text{ cm}^2 \text{ sr}\end{aligned}$$

## 7. 4. 2. 4b(a)

### Calculation Procedure

Because of the complexity (as explained above) of the calculation of the  $\Delta V$  signal, we are restricted here to describing the effects of the instrument parameters on the resulting SNR. Also, we are restricted to the one pollutant,  $SO_2$ , and to the atmospheric conditions which were assumed in the above calculation.

### Analytical Procedure

Step 1: Using known or typical values of the proposed instrument, calculate

$$G = \frac{\eta A_o D^*}{A_d A_f}$$

The typical values used in the above-referenced calculation (i. e.,

$$\eta = 0.01$$

$$A_d = 0.23. \text{ cm}^2$$

$$A_f = 4.17 \times 10^{-3} \text{ Hz} (= 1/4 t_c)$$

$$D^* (4 \mu\text{m}) = 3 \times 10^{11} \text{ w}^{-1} \text{ Hz}^{\frac{1}{2}} \text{ cm}$$

$$D^* (8 \mu\text{m}) = 10^{10} \text{ w}^{-1} \text{ Hz}^{\frac{1}{2}}$$

$$A_o = 0.143 \text{ cm}^2 \text{ sr})$$

can be used if actual values are not available.

Step 2: Using the value of G calculated in Step 1, calculate

$$k (4\mu\text{m}) = 1.39 \times 10^{10} / G$$

$$k (8\mu\text{m}) = 4.62 \times 10^9 / G$$

7.4.2.4b(b)

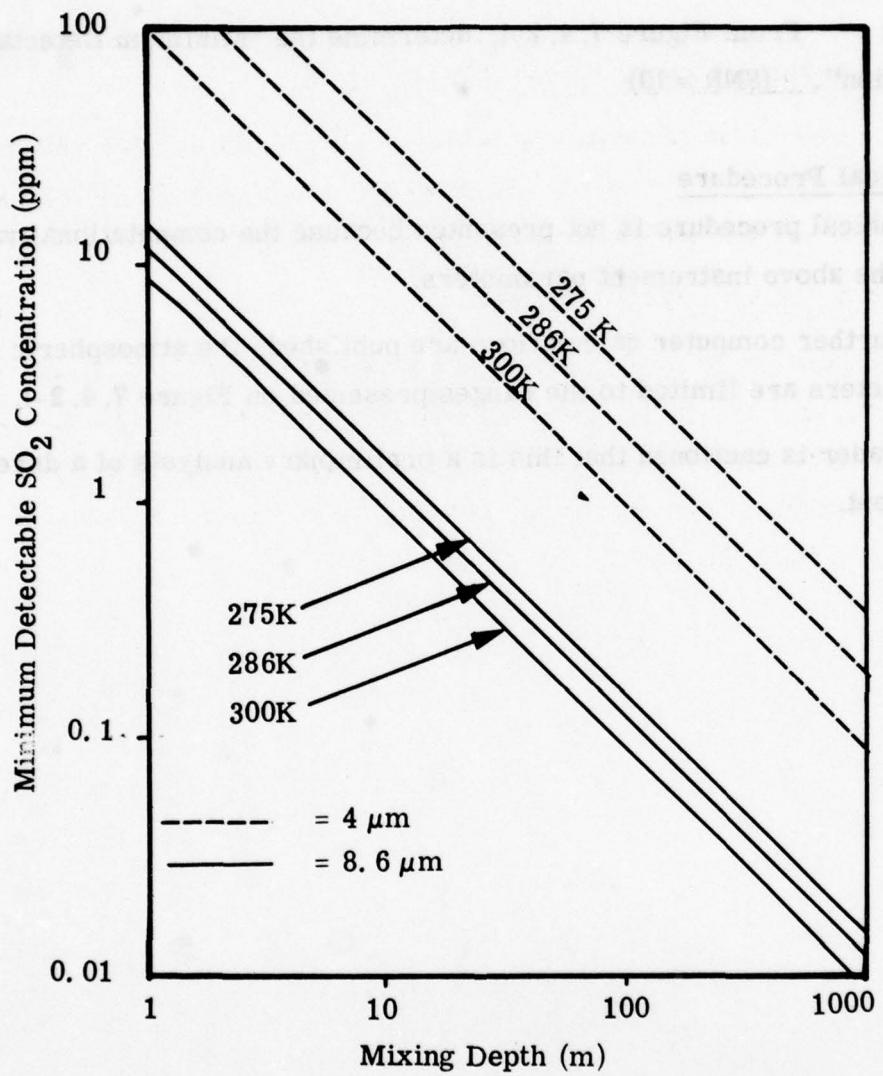
**Step 3:** From Figure 7.4.2-1, determine the "Minimum Detectable SO<sub>2</sub> Concentration". (SNR = 10)

Graphical Procedure

A graphical procedure is not presented because the computational variables are limited to the above instrument parameters.

Until further computer calculations are published, the atmospheric and pollutant parameters are limited to the ranges presented on Figure 7.4.2-1.

The reader is cautioned that this is a preliminary analysis of a developmental instrument.



**Figure 7. 4. 2-1.** SO<sub>2</sub> Concentration Versus Mixing Depth for a GFC Instrument with SNR - 10 at Two Different Wavelength Regions

7.4.2.5  
7.4.2.6a

**7.4.2.5 Special Performance Requirements**

The general requirements applicable to all remote monitors were described in Section 7.1.1. Special requirements applicable to particular pollutants are described in discussions of other monitors in Section 7.

**7.4.2.6 Data Analysis Procedures**

The concentration of the pollutant is related to the output signal ( $\Delta V$ ) of the GFC instrument directly by laboratory and/or field calibrations. Typical calibration curves are shown in Fig. 7.4.2-3. The atmospheric temperature and layer thickness must be known to estimate the mean concentration of the pollutant.

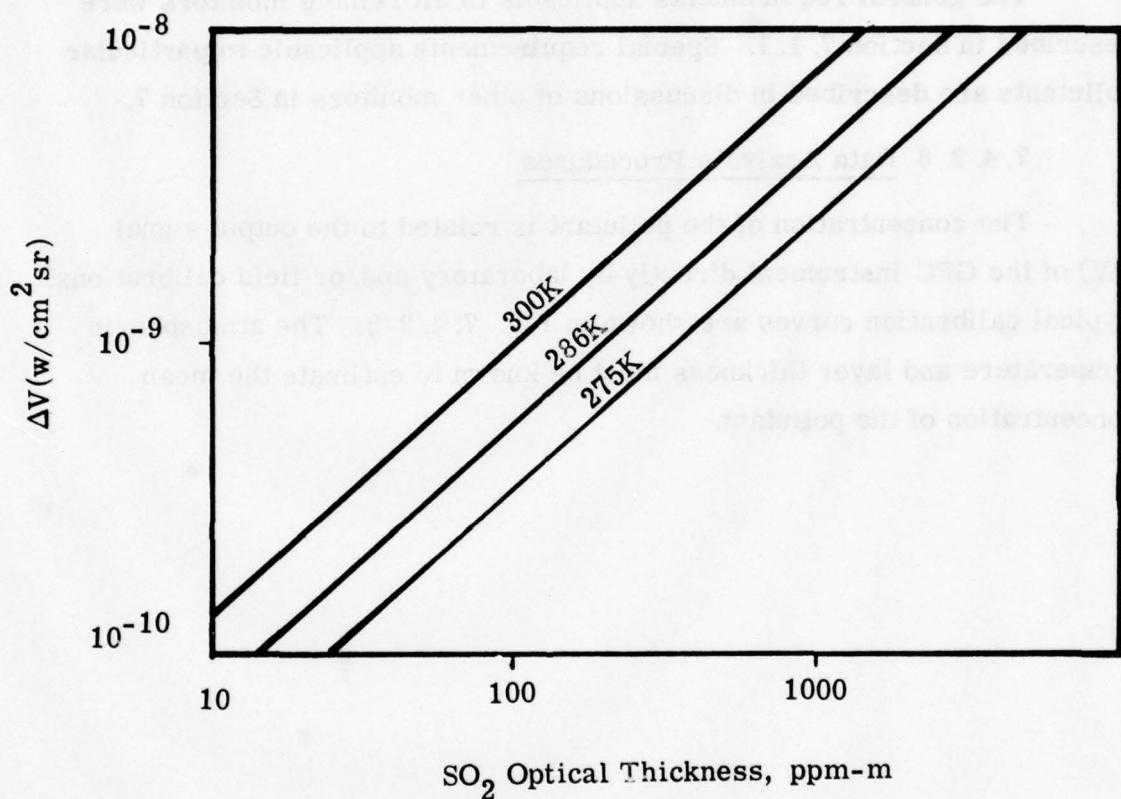


Figure 7. 4. 2-2. GFC Signal as a Function of  $\text{SO}_2$  Loading at 4  $\mu\text{m}$  for Three Temperatures

## REFERENCES

- (1) "Jet Aircraft Emissions and Air Quality in the Vicinity of the Los Angeles International Airport," Air Pollution Control District County of Los Angeles, CA., April 1971.
- (2) "An Air Pollution Impact Methodology for Airports and Attendant Land Use," Argonne National Laboratory, APTD-1470 (January 1973).
- (3) "Air Quality Measurement at Atlanta International Airport Before and During Experimental Aircraft Taxiing Operations" - Final Report, EF-330, GEOMET, Inc. (June 1974).
- (4) "Airport Vicinity Air Pollution Study," Argonne National Laboratory, FAA-RD-73-113 (December 1973).
- (5) "Air Pollution at Heathrow Airport, London," SAE-DOT Conf. Aircraft, Washington, D. C., February 8-10, 1971.
- (6) K. Zeller, EPA-LV, private communication, September 1975.
- (7) 40 CFR 50
- (8) "Federal Air Quality Control Regions," EPA, Office of Air Programs, Publ. No. AP-102, January 1972.
- (9) "Aircraft Emissions: Impact on Air Quality and Feasibility of Control," EPA (no number, no date given).
- (10) "Analysis of Aircraft Exhaust Emission Measurements," Cornell Aeronautical Laboratory, NTIS--PB 204-879 (October 1971).
- (11) "USAF Aircraft Pollution Emission Factors and LTO Cycles," D. F. Naugle, and S. R. Nelson, AFWL-TR-74-303, (February 1975).
- (12) M. Platt, et al., "The Potential Impact of Aircraft Emissions on Air Quality," NREC Report No. 1167-1, (December 1971)
- (13) D. M. Pote, et al., "Airport Vicinity Air Pollution Study", FAA-RD-73-113, (December 1973)

- (14) J. E. Norco, et al., "An Air Pollution Impact Methodology for Airports and Attendant Land Use," APTD-1470, EPA, (January 1973).
- (15) "Air Quality Display Model," TRW Systems Group, NTIS PB-189194, (November 1969).
- (16) D. M. Rote, et al., "A Generalized Air Quality Assessment Model for Air Force Operations," AFWL-TR-74-304, (February 1975).
- (17) M. Sittig, "Pollution Detection and Monitoring Handbook," Noyes Data Corporation, Park Ridge, N. J. (1974).
- (18) E. R. Bartle, et al., "Development of HCl and HF Detection System", AFRPL-TR-71-59.
- (19) D. Burch, EPA-650/2-73-030 (1973).
- (20) A. R. Barringer, Proc. 4th Symp. Rem. Sens. (1966).
- (21) J. A. Decker, Appl. Optics 10, 510 (1971).
- (22) W. K. McGregor, et al., CIAP Rep. DOT-TSC-OST-73-4, p. 214.
- (23) J. A. Hodgeson, et al., in "Analytical Methods Applied to Air Pollution Measurements," Ann Arbor Science, eds. R. K. Stevens and W. F. Herget (1974), p. 43.
- (24) E. D. Hinkley and A. R. Calawa, ibid., p. 55
- (25) L. G. Rosengren, Appl. Optics 14, 1960 (1975).
- (26) H. M. Segal, "Realistic Mixing Depths for Above Ground Aircraft Emissions", JAPCA 25, 1054 (1975).
- (27) H. W. Hiser, G. F. Andrews, and H. V. Senn, "Radar Measurement of Small Scale Turbulence and Thermal Stability in the Laser Atmosphere", JAPCA 25, 835 (1975).
- (28) J. Stuart Fordyce and Dean W. Sheibley, "Estimate of Contribution of Jet Aircraft Operations to Trace Element Concentration at or Near Airports", JAPCA 25, 721 (1975).

- (29) E. K. Bastress, "Impact of Aircraft Exhaust Emissions at Airports", Environ. Sci. Technol. 7, 811 (1973).
- (30) R. Dams, J. A. Robbins, K. A. Rahn, and J. W. Winchester, "Non-destructive Neutron Activation Analysis of Air Pollution Particulates", Anal. Chem. 42: 861 (1970).
- (31) R. E. Lee, Jr., S. S. Goranson, R. E. Ennone, and G. B. Morgan, "National Air Surveillance Cascade Impactor Network: II. Size Distribution Measurements of trace metal components," Environ. Sci. Technol. 6: 1025 (1972).
- (32) G. B. Morgan, G. Azolins, and E. C. Tabar, "Air Pollution Surveillance Systems", Science 170: 189 (Oct. 16, 1970).
- (33) R. B. King et al., Lewis Research Center, unpublished data obtained for the City of Cleveland.
- (34) R. T. H. Collis, and E. E. Uthe, "Mie Scattering Techniques for Air Pollution Measurement with Lasers", Opto-electronics 4, 87 (1972).
- (34a) R. M. Measures and G. Pilon, Opto-electronics 4, 141 (1972).
- (35) C. S. Cook, G. W. Bethke and W. D. Conner, Appl. Opt. 11, 1742 (1972).
- (36) W. D. Conner and J. R. Hodkinson, P. H. S. Publ. 999-AP-30 (1967).
- (37) W. Conner, EPA, private communication (1975).
- (38) S. Nakahara, K. Ito, A. Fuke, S. Komatsu, H. Inaba, T. Kobayashi, Opto-electronics 4, 169 (1972).
- (39) E. E. Uthe and W. B. Johnson, "Lidar Observations of the Lower Troposphere Aerosol Structure During BOMEX", Final Report, SRI Project 7929 (1971).
- (40) R. T. H. Collis, Applied Optics 9, 1782 (1970).
- (41) E. E. Uthe and R. J. Allen, Optical and Quantum Electronics 7, 121 (1975).

- (42) P. B. Russell and E. E. Uthe, "The Mt. Sutro Tower Aerosol and Radiation Study", paper presented at Fall Annual Meeting of the American Geophysical Union, San Francisco, CA., 12-17 December 1974.
- (43) P. B. Russell and E. E. Uthe, "The Mt. Sutro Tower Aerosol and Radiation Study", presented at the 7th International Laser Radar Conference, SRI, November 4-7, 1975.
- (44) J. D. Spinhirne, B. M. Herman, and J. A. Reagan, "Monitoring of Tropospheric Aerosol Optical Properties by Lidar", presented at the 7th International Laser Radar Conference, SRI, November 4-7, 1975.
- (45) J. A. Reagan, D. M. Byrne, B. M. Herman, and R. L. Peck, "New Observations of Tropospheric Aerosols Made with the University of Arizona Bistatic Lidar", presented at 7th International Laser Radar Conference, SRI, November 4-7, 1975.
- (46) J. A. Reagan, J. D. Spinhirne, D. M. Byrne, and R. L. Peck, "Atmospheric Particulate Properties Inferred from Lidar and Solar Radiometer Observations Compared with In-Situ Aircraft Measurements: A Case Study", presented at 7th International Laser Radar Conference, SRI, November 4-7, 1975.
- (47) E. M. Patterson, G. W. Grams, and D. A. Gillette, "An Analysis of Laser Radar Backscatter Profiles Obtained During a Rural Boundary Layer Experiment", presented at 7th International Laser Radar Conference, SRI, November 4-7, 1975.
- (48) J. J. DeLuisi, B. G. Schuster and R. K. Sato, Applied Optics 14, 1917 (1975).
- (49) S. T. Shipley, J. A. Weinman, "Design Considerations for a High Spectral Resolution Lidar", presented at 7th International Laser Radar Conference, SRI, November 4-7, 1975.
- (50) W. R. McNeil and A. I. Carswell, Applied Optics 14, 2158 (1975).
- (51) A. I. Carswell, S. R. Pal and J. S. Ryan, "Lidar Scattering in Turbid Media", presented at 7th International Laser Radar Conference, SRI, November 4-7, 1975.

- (52) R. W. L. Thomas and A. C. Holland, "A Monte Carlo Simulation of the Depolarization of Lidar Signals by Clouds", and "Maximum Sky Polarization: A supplement to Laser Atmospheric Studies—More Results", presented at 7th International Laser Radar Conference, SRI, November 4-7, 1975.
- (53) K. Sassen, "A Comparison of Hydrometeor Linear Depolarization Ratios from CW Laser and Lidar Systems", presented at 7th International Laser Radar Conference, SRI, November 4-7, 1975.
- (54) 39FR32094, September 4, 1974.
- (55) F. S. Harris, Jr., Appl. Optics 11, 2697 (1972).
- (55a) G. M. Hidy and S. K. Friedlander, "The Nature of the Los Angeles Aerosol", Proc. 2nd Intern. Clean Air Congr., eds. H. M. Englund and W. T. Beary, Academic Press, New York and London, p. 391 (1971).
- (56) M. Griggs, JAPCA 22, 356 (1972).
- (57) L. Elterman, Applied Optics 9, 1804 (1969).
- (58) Schotland, R. M., J. Appl. Meteorol. 13, 71 (1974).
- (59) C. B. Ludwig and M. Griggs, "Application of Remote Monitoring Techniques in Air Enforcement", Final Report, EPA 68-03-2137, SAI-75-638-LJ (April 1975).
- (60) K. W. Rothe, U. Brinkmann and H. Walther, Appl. Phys. 3, 115 (1974a).
- (61) K. W. Rothe, U. Brinkmann and H. Walther, Appl. Phys. 4, 181 (1974b).
- (62) W. B. Grant, R. D. Hake, Jr., E. M. Liston, R. C. Robbins and E. K. Proctor, Jr., Appl. Phys. Lett. 24, 550 (1974).
- (63) T. Igarashi, 5th Conference on Laser Radar Studies, Williamsburg, Virginia (June 1973).
- (64) S. Zaromb, Pittsburgh Conference, Cleveland (March 1974).

- (65) V. L. Granatstein, M. Rhinewine and A. H. Fitch, *Appl. Opt.* 12, 1511 (1973).
- (66) S. A. Ahmed, *Appl. Opt.* 12, 901 (1973).
- (67) R. L. Byer and M. Garbuny, *Appl. Opt.* 12, 1497 (1973).
- (68) W. B. Grant and R. D. Hake, Jr., *Journal of Applied Physics* 46, 3019 (1975).
- (69) H. Inomata and T. Igarashi, Radio Research Laboratories, Tokyo, Preprint, private communication (1974).
- (70) K. Asai and T. Igarashi, Preprint, private communication (1974).
- (71) T. Kobayasi and H. Inaba, *Optical and Quantum Electronics* 7, 319 (1975).
- (72) J. M. Hoell, Jr., W. R. Wade, and R. T. Thompson, Jr.: Remote Sensing of Atmospheric SO<sub>2</sub> Using the Differential Absorption Lidar Technique. Proceedings of the International Conference on Environmental Sensing and Assessment, Las Vegas, Nevada, September 14-19, 1975.
- (73) W. R. Wade, J. M. Hoell, Jr., and R. T. Thompson, Jr., "A Lidar System for the Measurement of Tropospheric SO<sub>2</sub> Using the Dial Technique", presented at 7th International Laser Radar Conference, SRI, November 4-7, 1975.
- (74) E. E. Remsberg, L. Gordley, S. K. Poultney and R. T. Thompson, "Analysis of Differential Absorption Lidar Measurements from Shuttle", presented at 7th International Laser Radar Conference, SRI, November 4-7, 1975.
- (75) M. L. Wright, E. K. Proctor, L. S. Gasiorek, and E. M. Liston: A Preliminary Study of Air Pollution Measurement by Active Remote Sensing Techniques. Contract Report NAS1-11657 (1975).
- (76) C. H. Bair and F. Allario, "Analysis of the Sensitivity of Near IR Dial for Measurements of HCl in the Ground Cloud of SRM's and for Profiling Atmospheric Pollutants", presented at 7th International Laser Radar Conference, SRI, Nov. 4-7, 1975.

- (77) R. K. Dumbauld, R. J. Bjorklund and J. F. Bowers, "NASA/MSFC Multilayer Diffusion Models and Computer Program for Operational Prediction of Toxic Fuel Hazards", NASA CR-129006 (June 1973).
- (78) T. J. McIlrath, M. B. Marris and R. W. Gammon, "Tunable Laser for Water Vapor Lidar", presented at 7th International Laser Radar Conference, SRI, Nov. 4-7, 1975.
- (79) T. Wilkerson, L. Cotnoir III and G. Schwemmer, "Water Vapor Lidar: Calibration and Simulation", presented at 7th Int'l Laser Radar Conference, SRI, November 4-7, 1975.
- (80) D. Herriott and H. J. Schulte, *Appl. Optics* 4, 883 (1965).
- (81) E. R. Murray, R. D. Hake, Jr., J. E. van der Laan, and J. G. Hawley, "Atmospheric Water Vapor Measurements with a 10- $\mu\text{m}$  Dial System", presented at 7th Int'l Laser Radar Conference, SRI, Nov. 4-7, 1975; *App. Physics Ltrs.* 28, 542.
- (82) W. B. Grant, J. G. Hawley, R. D. Hake, Jr., and R. G. March, "Backscatter Fluctuations Observed with a Variable-Delay Dual-Pulse Lidar", presented at 7th Int'l Laser Radar Conference, SRI, Nov. 4-7, 1975.
- (83) J. B. Marling, J. G. Hawley, E. M. Liston, and W. B. Grant, "Lasing Characteristics of Seventeen Visible-Wavelength Dyes Using a Coaxial-Flashlamp-Pumped Laser", *Applied Optics* 13, 2317 (1974).
- (84) H. Kildal and R. L. Byer, *Proc. IEEE* 59, 1644 (1971).
- (85) T. Hirschfeld and S. Klainer, "Remote Raman Spectroscopy as a Pollution Radar", *Optical Spectra*, p. 63 (July/August 1970).
- (86) C. M. Penney, L. M. Goldman, and M. Lapp, "Raman Scattering Cross Sections," *Nature Physical Science* 235, 110 (1972).
- (87) D. G. Fouche and R. K. Chang, "Relative Raman Cross Section for N<sub>2</sub>, O<sub>2</sub>, CO, CO<sub>2</sub>, SO<sub>2</sub>, and H<sub>2</sub>S," *Appl. Phys. Letters* 18, 579 (1971).
- (88) W. Arden, et. al., Remote Raman Detection Study Instrument, 6th Quarterly Progress Report, Edgewood Arsenal Contract DAAA15-70-C-0418 (1972).

- (89) H. P. DeLong, "Air Pollution Field Studies with a Raman Lidar", Optical Engr. 13, 5 (1974).
- (90) H. Inaba and T. Kobayasi, Opto-Electr. 4, 101 (1972).
- (91) S. H. Melfi, J. D. Lawrence, and M. P. McCormick, "Observation of Raman Scattering by Water Vapor in the Atmosphere," Appl. Phys. Letters 15, 295 (1969).
- (92) W. H. Smith, "A New Method for the Detection of Raman Scattering from Atmospheric Pollutants", Opto-Electr. 4, 161 (1972).
- (93) J. J. Barrett, "The Use of a Fabry-Perot Interferometer for Studying Rotational Raman Spectra of Gases" in Laser Raman Gas Diagnostics, p. 63, eds. M. Lapp and C. M. Penney, Plenum Press, New York and London; (1974).
- (94) S. M. Klainer, "Advances in Remote Gas Analysis Using Fabry-Perot Techniques", p. 86 in Proc. Soc. Photo-Opt. Instr. Eng., Vol. 49, Impact of Lasers in Spectroscopy, San Diego, CA., August 19-20, 1974.
- (95) J. A. Gelbwaches and M. Birnbaum, Applied Optics 12, 2442 (1973).
- (96) D. A. Leonard and B. Caputo, "A Single-ended Atmospheric Transmissometer", Opt. Engr. 13, 11 (1974).
- (97) D. D. Dylis, "A Raman Technique for the Remote Measurement of Aqueous Acid Solutions," p. 156 in Proc. Soc. Photo-Opt. Instr. Eng., Vol. 49, Impact of Lasers in Spectroscopy, San Diego, CA., August 19-20, 1974.
- (98) S. K. Poultney, M. L. Brumfield and J. H. Siviter, Jr., "Quantitative Remote Measurements of Pollutants from Stationary Sources Using Raman Lidar", presented at the 7th International Laser Radar Conference, SRI, November 4-7, 1975.
- (99) D. A. Leonard, "Raman and Fluorescence Measurements of Combustion Emission," p. 110 in Proc. Soc. Photo-Opt. Instr. Eng., Vol. 49, Impact of Lasers in Spectroscopy, San Diego, CA., August 19-20, 1974.
- (100) Lt. G. E. Bresowar and D. A. Leonard, "Measurement of Gas Turbine Exhaust Pollutants by Raman Spectroscopy," AIAA Paper No. 73-1276 (Nov. 1973).

- (101) V. E. Derr and C. G. Little, Appl. Optics 9, 1976 (1970).
- (102) T. Hirschfeld, E. R. Schildkraut, H. Tannenbaum and D. Tannenbaum, Appl. Phys. Lett. 22, 38 (1973).
- (103) P. F. Williams, D. L. Rousseau, and S. H. Dworetsky, Phys. Rev. Lett. 32, 196 (1974).
- (104) H. Rosen, P. Robrish and O. Chamberlain, Applied Optics 14, 2703 (1975).
- (105) W. Holzer, W. F. Murphy and H. J. Bernstein, J. Chem. Phys. 52, 399 (1970).
- (106) C. C. Wang and L. I. Davis, Phys. Rev. Lett. 32, 349 (1974).
- (107) R. L. St. Peters, S. D. Silverstein, W. M. Morey and D. J. Taylor, "Raman Scattering Studies," General Electric, Final Technical Report SRD-73-033 (February 1973).
- (108) C. M. Penney, "Light Scattering and Fluorescence in the Approach to Resonance—Stronger Probing Processes," p. 191, in "Laser Raman Gas Diagnostics," ed. M. Lapp and C. M. Penney, Plenum Press, New York and London, (1974).
- (109) W. Kiefer, "Penney Discussion", p. 215 in "Laser Raman Gas Diagnostics," ed. M. Lapp and C. M. Penney, Plenum Press, New York and London, (1974).
- (110) M. L. Wright, E. K. Proctor, L. S. Gasiorek and E. M. Liston, "A Preliminary Study of Air Pollution Measurement by Active Remote-Sensing Techniques," NASA CR-132724 (June 1975).
- (111) R. L. Byer, Opt. Quant. Electr. 7, 147 (1975).
- (112) M. R. Bowman, A. J. Gibson and M. C. W. Sandford, Nature 221, 456 (1969).
- (113) A. J. Gibson, J. Sci. Instr. 2, 802 (1969).
- (114) A. J. Gibson and M. C. W. Sandford, Nature 239, 509 (1972).
- (115) F. Felix, W. Keenliside, G. Kent and M. C. W. Sandford, Nature 246, 345 (1973).

- (116) S. Nakahara, K. Ito and S. Ito, Abstracts from 5th Conference Laser Radar Studies, Williamsburg, Virginia (June 1973).
- (117) M. C. Fowler and P. J. Berger, "Feasibility Study of the Use of Resonance Scattering for the Remote Detection of  $\text{SO}_2$ ", EPA-650/2-74-020 (Jan. 1974).
- (118) J. W. Robinson and J. D. Dake, Spectr-Lett. 6, 685 (1973).
- (119) J. W. Robinson and J. D. Dake, Anal. Chem. Acta 71, 277 (1974).
- (120) I. M. Pikus, H. W. Goldstein and T. R. Riethof, "The Remote Measurement of NO from an Airplane or Space Platform," AIAA Paper 71-1112 (Nov. 1971).
- (121) R. T. Menzies, Appl. Optics 10, 1532 (1971).
- (122) C. M. Penney, W. W. Morey, R. L. Peters, S. D. Silverstein, M. Lapp and D. R. White, NASA CR-132363 (Sept. 1973).
- (123) J. A. Gelbwachs, M. Birnbaum, A. W. Tucker and C. L. Finder, Opto-electronics 4, 155 (1972).
- (124) J. A. Gelbwachs and M. Birnbaum, Appl. Optics 12, 2442 (1973).
- (125) D. G. Fouche and R. K. Chang, Phys. Rev. Lett. 29, 536 (1972).
- (126) R. L. St. Peters, S. D. Silverstein, M. Lapp, and C. M. Penney, Phys. Rev. Lett. 30, 191 (1973).
- (127) R. L. St. Peters and S. D. Silverstein, Opt. Commun. 7, 193 (1973).
- (128) M. Berjot, M. Jacon and L. Bernard, Opt. Comm. 4, 117 (1971); Can. J. Spectr. 17, 60 (1972).
- (129) P. Robrish, H. J. Rosen, and O. Chamberlain, "Observation of a Continuous Transition from Resonance Raman Scattering to Fluorescence," U. C. Berkeley (submitted for publication).
- (130) E. L. Baardsen and R. W. Terhune, Appl. Phys. Lett. 21, 209 (1972).
- (130a) M. L. Streiff and C. B. Ludwig, "Remote Sensing of Air Pollution in Urban Areas," EPA-650/2-73-026 (August 1973).
- (131) T. Hirschfeld, "Tunable Laser, Good and Bad," Optical Spectra, p. 23 (Aug. 1974).

- (131a) J. Kuhl and W. Schmidt, Appl. Phys. 3, 251 (1974)
- (132) E. D. Hinkley, "Development of In-Situ Prototype Diode Laser System to Monitor SO<sub>2</sub> Across the Stack," MIT-Lincoln Laboratory, Final Report, EPA-R2-73-218 (May 1973).
- (133) G. K. Klauminzer, "New Dye Laser Applications," Electro-Opt. Sys. Des., p. 25 (Dec. 1974).
- (134) O. R. Wood, "High Pressure Molecular Lasers," Proc. IEEE 62, 355 (1974).
- (135) R. V. Hess and R. K. Seals, Jr., "Applications of Tunable High Energy/Pressure Pulsed Lasers to Atmospheric Transmission and Remote Sensing," NASA TM X-7201 (Sept. 1974).
- (136) R. L. Abrams and W. B. Bridges, "Characteristics of Sealed-Off Waveguide CO<sub>2</sub> Lasers," IEEE J. Quant. Electr. QE9, 940 (1973).
- (137) R. L. Byer, "Parametric Oscillators," from Laser Spectroscopy, eds. R. G. Brewer and A. Mooradian, Plenum Pub. Co., New York (1974).
- (138) R. L. Byer, R. L. Herbst, and R. N. Fleming, "A Broadly Tunable IR Source," Appl. Phys. Dept., Stanford University, private communication, (1975).
- (139) C. K. N. Patel, "Tunable Spin-Flip Raman Laser and High Resolution IR Spectroscopy," presented at the Pittsburgh Conf. in Cleveland, Paper No. 325, March 4-8 (1974).
- (140) "Spin-Flip Device Could Play Role in SST Story," Electronics, p. 32, (Sept. 13, 1971).
- (141) Reserved
- (142) Reserved
- (143) W. A. McClenny, R. E. Baumgardner, Jr., F. W. Baity, and R. A. Gray, JAPCA 24, 1044 (1974).
- (144) T. B. Hirschfeld, Opt. Engineering 13, 15 (1974).

- (145) J. J. Ball and R. A. Keller, JAPCA 25, 631 (1975).
- (146) D. C. O'Shea and L. G. Dodge, Appl. Optics 13, 1481 (1974).
- (146a) C. B. Ludwig, R. Bartle, and M. Griggs, "Study of Air Pollutant Detection by Remote Sensors," NASA CR-1380 (July 1969).
- (147) Z. Kucerovsky, E. Brannen, K. C. Paulekat and D. G. Rumbold, J. Appl. Meteor. 12, 1387 (1973).
- (148) S. E. Craig, D. R. Morgan, D. L. Roberts and L. R. Snowman, "Development of a Gas Laser System to Measure Trace Gases by Long Path Absorption Techniques," EPA-650/2-74-046a, June 1974.
- (149) W. A. McClenny, F. W. Baity, Jr., R. E. Baumgardner, Jr., R. A. Gray, R. J. Gillmeister and L. R. Snowman, "Development of a Gas Laser System to Measure Trace Gases by Long Path Absorption Techniques, Vol. II - Field Evaluation of Gas Laser System for Ozone Monitoring," EPA-650/2-74-046-b (July 1974).
- (150) E. D. Hinkley and R. T. Ku, "Diode Laser Multi-Pollutant Ambient Air Monitoring," NSF/RANN/IT/GI-37603 (June 1974).
- (151) R. T. Ku, E. D. Hinkley, and J. O. Sample, Appl. Optics 14, 854 (1975).
- (152) E. D. Hinkley, "Bistatic Monitoring of Gaseous Pollutants with Tunable Semiconductor Lasers," presented at the 1974 Pittsburgh Conf. on Anal. Chem. Appl. Spectr., Cleveland, Ohio (March 1974).
- (153) E. D. Hinkley and R. T. Ku, "Long-Path Ambient-Air Monitoring with Tunable Lasers—Participation in the St. Louis Regional Air Pollution Study (RAPS) of EPA," Proc. 2nd Ann. NSF-RANN Trace Contaminants Conf., Asilomar, CA (Aug. 1974).
- (154) R. T. Menzies and M. S. Schumate, JPL, private communication, (Sept. 1975).
- (155) R. T. Menzies and M. S. Schumate, Science 184, 571 (1974).
- (156) R. T. Menzies and M. T. Chahine, Appl. Optics 13, 2840 (1974).

- (157) S. H. Melfi, G. B. Morgan, J. L. Guagliardo and J. Koutsandreas, Proc. IEEE, National Aerospace and Electr. Conf., Dayton, Ohio (May 1974).
- (158) R. K. Selas and C. H. Bair, ISA JSP 6675, presented at 2nd Joint Conf. Sens. Env. Pollutants, Washington, D. C. (Dec. 1973).
- (159) L. R. Snowman and R. J. Gillmeister, "A Laser Policeman for Dirty Air," Optical Spectra, p. 30 (June 1972).
- (160) "3-D Study Provides Look at Upper Atmosphere," California Air Resources Board, Bulletin 6, 7 (May 1975).
- (161) "Laser Safety Guide," Laser Safety Committee of the Laser Institute of America, 4100 Executive Park Drive, Cincinnati, Ohio 45241 (Issued in 1974).
- (162) J. Topping, "Errors of Observation and Their Treatment," Science Paperbacks, Chapman and Hall LTD, 3rd Ed. (1962).
- (163) L. R. Snowman and R. J. Gillmeister, "Infrared Laser System for Extended Area Monitoring of Air Pollution," AIAA Paper 71-1059.
- (164) E. R. Ochs and R. S. Lawrence, ESSA Tech. Report ERL 106-WP16, Boulder, Colorado (Febr. 1969).
- (165) M. L. Streiff and C. L. Claysmith, "Design and Construction of a System for Remote Optical Sensing of Emissions," EPA-R2-72-052 (Oct. 1972).
- (166) "Air Pollution Measurements in the Infrared," General Dynamics, Electro Dynamic Division, TM 6-125PH-336 (Sept. 1971), included as Appendix I in Ref. 130a.
- (167) G. N. Plass, J. Opt. Soc. Am. 48, 690 (1958).
- (167a) S. S. Penner, "Quantitative Molecular Spectroscopy and Gas Emissivities," Addison-Wesley Publishing Co., Inc., Reading, Mass. (1959).
- (168) C. B. Ludwig, Appl. Optics 10, 1057 (1971).
- (169) V. E. Derr, M. H. Ackley, M. J. Post, and R. F. Calfee, "Calculation of the Concentrations of Atmospheric Gases from Long Path Infrared Absorption Spectra by a Least Squares Method," under Contract Agreement No. EPA-IAG-077(D).

- (170) R. A. Sawyer, "Experimental Spectroscopy," Dover Publications, Inc., New York, 3rd Edition (1963).
- (171) J. A. Decker, Jr., *Appl. Optics* 10, 510 (1971).
- (172) Larson, N. M., Crosmun, R., and Talmi, Y., *Appl. Opt.* 13, 2662, (1974).
- (173) L. Mertz, "Transformation in Optics," Wiley, New York (1965).
- (174) W. H. Steel, "Interferometry," Cambridge U. P., Cambridge (1967).
- (175) L. L. Acton, M. Griggs, G. D. Hall, C. B. Ludwig, W. Malkmus, W. D. Hesketh and H. Reichle, "Remote Measurement of Carbon Monoxide by a Gas Filter Correlation Instrument," *AIAA J.* 11, 899 (1973).
- (176) C. B. Ludwig, M. Griggs, W. Malkmus and E. R. Bartle, "Air Pollution Measurements from Satellites," NASA CR-2324 (Nov. 1973).
- (177) "Development of Gas Filter Correlation Instruments for Extended Area Stationary Source Gaseous Pollutant Measurements," EPA Contract 68-02-1798.
- (178) Barnes, H. M., Herget, W. F. and Robbins, R. "Analytical Methods Applied to Air Pollution Measurements," p. 245, Ann Arbor Science Publishers, Inc., (August 1974).
- (179) W. F. Herget, H. M. Barnes, Jr., C. B. Ludwig and G. W. Ashley, "Infrared Spectra of Pollutant Emissions from Various Stationary Sources," AIAA Paper No. 71-1082 (Nov. 1971).
- (180) A. Prostak and R. H. Dye, "Long-Path Spectrophotometric Instrumentation for In-Situ Monitoring of Gaseous Pollutants in the Urban Atmosphere," Bendix Aerospace Systems Division, BSR 3027 (Oct. 1970).
- (180a) E. D. Hinkley and P. L. Kelley, "Detection of Air Pollutants with Tunable Diode Lasers," *Science*.
- (181) E. R. Bartle, "Infrared Sensor for the Remote Monitoring of SO<sub>2</sub>," EPA-650/2-75-041 (May 1975).
- (182) E. D. Hinkley, "Tunable Infra-red Lasers and Their Applications to Air Pollution Measurements," *Opto-electronics* 4, 69 (1972).

- (183) R. T. Menzies, "Remote Sensing with Infared Heterodyne Radiometers," Opto-electronics 4, 179 (1972).
- (184) R. T. Menzies and M. S. Shumate, "Air Pollution: Remote Detection of Several Pollutant Gases with a Laser Heterodyne Radiometer," Science 184, 570 (1974).
- (185) R. K. Seals, "Analysis of Tunable Laser Heterodyne Radiometry: Remote Sensing of Atmospheric Gases," AIAA J. 12, 1118 (1974).
- (186) M. C. Teich, Proc. IEEE 56, 37 (1968).
- (187) A. E. Siegman, Proc. IEEE 54, 1350 (1966).
- (188) R. T. Menzies, Appl. Optics 10, 1532 (1971).
- (189) H. Walter, Jr. and D. Flanigan, Appl. Optics 14, 1423 (1975).
- (190) B. Noble, "Applied Linear Algebra," Prentice-Hall, Englewood Cliffs, N. J. (1969).
- (191) D. Flanigan and H. DeLong, Appl. Optics 10, 51 (1971).
- (192) A. R. Barringer and J. P. Schock, Proc. 4th Symp. Rem. Sens. Environ., U. Michigan, p. 779 (1966).
- (193) G. S. Newcomb and M. M. Millian, IEEE Trans. Geosci. Electr. GE-8, 149 (1970).
- (194) M. M. Millian, S. J. Townsend and J. Davies, "Study of the Barringer Refractor Plate Correlation Spectrometer as a Remote Sensing Instrument," Toronto, UTIAS Report, No. 146 (August 1970).
- (195) C. R. McCreight and C. L. Tien, "Interpretation Problems in the Correlation-Mash Sensing Technique," Paper No. 71-1061, Joint Conference on Sensing of Environmental Pollutants, Palo Alto, California (Nov. 8-10, 1971).
- (196) C. B. Ludwig, M. Griggs, W. Malkmus and E. R. Bartle, Appl. Optics 13, 1494 (1974).
- (197) R. A. McClatchey, W. S. Benedict, S. A. Clough, D. E. Burch, R. F. Calfee, K. Fox, L. S. Rothman, J. S. Garing, "AFCRL Atmospheric Absorption Line Parameters Compilation," AFCRL-TR-73-0096 (26 Jan. 1973).

- (198) J. N. Hamilton, J. A. Rowe and D. Anding, "Atmospheric Transmission and Emission Program," Aerospace Rep. No. TOR-0073(3050-02)-3 (15 June 1973).
- (199) J. E. A. Selby and R. A. McClatchey, "Atmospheric Transmittance from 0.25 to 28.5  $\mu$ m: Computer Code LOWTRAN 2," AFCRL-72-0745 (29 Dec. 1972).
- (200) H. J. Bolle, "The Influence of Atmospheric Absorption and Emission on Infrared Detection Range," Infrared Physics 5, 115 (1965).
- (201) M. Gutnick, "Aids for Computing Stratospheric Moisture," GRD Research Notes No. 50, AFCRL 203 (1961).
- (202) A. E. Siegman, Appl. Optics 5, 1588 (1966).
- (203) M. C. Teich, Proc. IEEE 56, 37 (1968).
- (204) W. L. Smith, Appl. Optics 9, 1993 (1970).
- (205) J. Y. Wang, J. Atmos. Sci. 31, 513 (1974).
- (206) A. Betz, "Laser Heterodyne Spectroscopy in Astronomy," Paper FB7-1, presented at "Applications of Laser Spectroscopy," Spring Conf. of Opt. Soc. Amer. at Anaheim, Calif., (March 19-21, 1975).
- (207) M. M. Abbas, M. J. Mumma, T. Kostiak and D. Buhl, "Sensitivity Limits of an Infrared Heterodyne Spectrometer for Astrophysical Applications," Appl. Optics 15, 427 (1976).
- (208) A. J. Hoffman, T. C. Curran, T. B. McMullen, W. M. Cox, and W. F. Hunt, Jr., "EPA's Role in Ambient Air Quality Monitoring," Science 190, 243 (1975).
- (209) "Ambient Air Monitoring Reference and Equivalent Methods," 40FR7042 (18 Feb. 1975).
- (210) 41FR3893 (January 27, 1976).
- (211) 41 FR5144 (February 4, 1976).
- (212) 41FR11263 (March 17, 1976).

- (213) "Guideline Specifications for the Development of Instruction Manuals for Automatic Air Monitoring Instruments," National Technical Information Service, U. S. Department of Commerce, 5285 Port Royal Road, Springfield, Virginia 22151.
- (214) An example manual based on the above report and titled "Fully Proceduralized Instruction Manual for the Bendix Ozone Monitor, Model 8002" is available from the same source.
- (215) A. Daniels and W. Bach, "Simulation of the Environmental Impact of an Airport on the Surrounding Air Quality," J. Air. Poll. Contr. Ass. 26, 339-344 (1976).
- (216) A. Daniels, R. H. Jones, and W. Back, "Determination of Patterns of Average and Maximum Air Pollutant Levels in Urban Areas," Proc. Conf. Urban Env. and 2nd Conf. Biomet. 114-119 (1972).
- (217) R. Jones, A. Daniels, and W. Bach, "Fitting a Circular Distribution to a Histogram," J. Appl. Meteorol. 15: (1976).
- (218) L. M. Shabad and G. A. Smirnov, "Aircraft Engines as a Source of Carcinogenic Pollution of the Environment," Atmos. Environ. 6:153(1972).
- (219) J. A. Fay, "Air Pollution from Future Giant Jetports," Paper No. 70-78, 63rd Annual Meeting, APCA, St. Louis, 1970.
- (220) R. P. Carter and C. J. Gregory, "A Mathematical Diffusion Model with Respect to a Moving Aircraft," Paper No. 71-129, 64th Annual Meeting, APCA Atlantic City, 1971.
- (221) R. E. George, J. S. Nevitt, and J. A. Verssen, "Jet Aircraft Operations: Impact on the Air Environment," J. Air Poll. Control Assoc. 22:509 (1972).
- (222) R. Cirillo, J. F. Tschanz, and J. E. Camaioni, "Aircraft Control Measures for Emission Reduction," J. Air Poll. Contr. Ass. 26, 500 (1976).
- (223) I. T. Wang, D. M. Rote, L. A. Conley, "Airport Vicinity Air Pollution Study--Model Application and Validation and Air Quality Impact Analysis at Washington National Airport," Argonne National Laboratory, Report No. FAA-RD-74-132, Federal Aviation Administration, Washington, D. C., July 1974.

- (224) L. E. Wangen, et al., "A Generalized Air Quality Assessment Model for Air Force Operations--An Operator's Guide," Argonne National Laboratory, Report No. TR-74-54, Air Force Weapons Laboratory, Kirtland AFB, N. M., to be published.
- (225) D. M. Rote and L. E. Wangen, "A Generalized Air Quality Assessment Model for Air Force Operations--Technical Report," Argonne National Laboratory, Air Force Weapons Laboratory, Kirtland AFB, N. M., to be published.
- (226) J. T. MacWaters, R. C. Koch, and S. D. Thayer, "Air Quality Measured at Atlanta International Airport before and during Experimental Aircraft Taxiing Operations," GEOMET Report No. EF-330, June 1974.
- (227) "Review of Atlanta Aircraft Ground Emissions Control Demonstration," Mitre Corp., McLean, Va., to be published.
- (228) R. R. Cirillo, J. F. Tschanz, J. E. Camaioni, "An Evaluation of Strategies for Airport Air Pollution Control," Report No. EPA-450/3-75-052, U. S. Environmental Protection Agency, Research Triangle Park, N. C., January 1975.
- (229) J. S. Nader, F. Jaye and W. Conner, "Performance Specifications for Stationary-Source Monitoring Systems for Gases and Visible Emissions," EPA-650/2-74-013 (January 1974).
- (230) Request for Proposal, EPA, DU-76-A157 (April 23, 1976).
- (231) E. E. Hughes, "Development of Standard Reference Materials for Air Quality Measurement," presented at Instr. Soc. Am., Instrumentation-Automation Conference, New York, N. Y., October 28-31, 1974.
- (232) H. G. McAdie and F. J. Hopton, "The Need for Practical Standards in Air Pollution Measurement," American Laboratory (December 1975).
- (233) R. J. Bryan, P. C. Kochis, J. W. Boyd, M. L. McQueary and R. L. Norton, "Guidelines for Enforcement and Surveillance of Supplementary Control Systems," EPA-340/1-75-008 (September 1975).  
(The material dealing with meteorological instruments is excerpted from the 1975 Revision of the Air Pollution Training Institute, Course 435, Atmospheric Sampling, Chapter XXIII).

- (234) E. O. Doeblin, Measurement Systems: Application and Design, McGraw-Hill Co., New York.
- (235) E. W. Hewson, "Meteorological Measurements," Air Pollution, Vol. II, New York, Academic Press.
- (236) W. E. K. Middleton and A. F. Spilhaus, Meteorological Instruments, Toronto, University of Toronto Press, 1953.
- (237) A. C. Stern, Editor, Air Pollution Second Edition Vol. II, New York, Academic Press, 1968.
- (238) R. H. Dieck, and J. H. Elwood, "The Assessment of Emission Analysis Accuracy," presented at the 67th Annual APCA Meeting in Denver, CO., June 9-13, 1974.
- (239) P. K. Stein, "Classification Systems for Transducers and Measuring Systems," Symposium on Environmental Measurements, U. S. Dept. HEW, July 1964.
- (240) T. J. Lockhart, "Bivanes and Direct Turbulence Sensors," Meteorology Research Inc., MRI 170 Pa 928, June 1970.
- (241) H. Klingenbergs, M. Fock, K. -H. Lies and L. Pazsitka, "A Critical Study of the United States Exhaust Emission Certification Test--Error Analysis for the Test Procedure," presented at the 67th Annual APCA Meeting in Denver, CO., June 9-13, 1976.
- (242) R. T. Ku and E. D. Hinkley, "Long-Path Monitoring of Atmospheric Carbon Monoxide", (1975 RAPS, St. Louis, Missouri), NSF/RANN/IT/GI-37603, (April 1976).
- (243) E. D. Hinkley, "Laser Spectroscopic Instrumentation and Techniques: Long-Path Monitoring by Resonance Absorption", Optical and Quantum Elec. 8, 155-167 (1976).
- (244) "Pollution Monitor has 10 km Range", Industrial Research, p. 14 (July 1976).
- (245) AWST, (May 31, 1976).
- (246) W. Herget, "Long-Path Measurements of CO Concentrations at Williams Air Force Base", Interim Report, (April 19, 1976).

- (247) R. H. Dieck and J. H. Elwood, "The Assessment of Emission Analysis Accuracy", JAPCA 25, 845 (1975).
- (248) M. C. Natrella, "Experimental Statistics", NBS Handbook Number 91, (1963).
- (249) E. R. Murray, "Remote Measurement of Gases Using Discretely Tunable Infrared Lasers", presented at the 20th SPIE Symposium, Paper 95-15, San Diego, CA., August 24-27, (1976); Optical Engineering 16, 284.
- (250) D. J. Spencer, G. C. Denault, and H. H. Takimoto, "Atmospheric Gas Absorption at DF Laser Wavelengths", Appl. Opt., Vol. 13, p. 2855 (1974).
- (251) R. T. Menzies and M. S. Shumate, "Remote Measurements of Ambient Air Pollutants with a Bistatic Laser System", Appl. Opt. 15, 2080 (1976).
- (252) P. Beckmann and A. Spizzichino, "The Scattering of Electromagnetic Waves from Rough Surfaces", (Pergamon, New York, 1963)
- (253) G. T. Ruck, D. E. Barrick, W. D. Stuart and C. K. Krickbaum, "Radar Cross Section Handbook", (Plenum, New York, Vol. 2, Chap. 9, (1970).
- (254) N. George, A. Jain, Appl. Phys. 4, 201 (1974).
- (255) N. George, A. Jain, and R. D. Melville, Jr., Appl. Phys. 6, 65 (1975).
- (256) "Handbook of Lasers", ed. R. J. Pressley, The Chemical Rubber Co. (1971).
- (257) "Laser Focus: 1976 Buyer's Guide", Adv. Technology Publ., Inc., Newton, Mass. (February 1976).
- (258) R. A. Brandewie and W. C. Davis, "Parametric Study of a 10.6- $\mu$ m Laser Radar", Appl. Opt. 11, 1526 (1972).
- (259) H. Koschmieder, Beitr. Phys. Atmos. 12, 33, 171 (1924)

- (260) R. J. Charlson, N. C. Ahlquist, H. Selvidge, and P. B. MacCready, Jr., "Monitoring of Atmospheric Aerosol Parameters with the Integrating Nephelometer," *J. Air Poll. Control Assoc.* 19, 937 (1969).
- (261) W. Fett, *Beitr. Phys. Atmos.* 40, 262 (1967).
- (262) J. S. Curcio, G. L. Knestrick, and T. H. Cosden, "Atmospheric Scattering in the Visible and Infrared," *NRL Rep. 5567*, Washington, D. C. (1961).
- (263) L. Elterman, "Relationship Between Vertical Attenuation and Surface Meteorological Range," *Appl. Optics* 9, 1804 (1970).
- (263a) L. Elterman, "UV, Visible and IR Attenuation for Altitudes to 50 km, 1968," *AFCRL-68-0153* (Apr. 1968).
- (264) M. P. McCormick and W. H. Fuller, Jr., "Lidar Applications to Pollution Studies," *AIAA Paper No. 71-1056*, Joint Conf. Sens. Environm. Pollutants, Palo Alto, CA (Nov. 1971).
- (265) J. A. Curcio, L. F. Drummetter and T. H. Cosden, "The Absorption Spectrum of the Atmosphere from 4400 to 5500 Å," *NRL Report 4669* (9Decl955) (AD81133).
- (266) J. A. Curcio and G. L. Knestrick, "An Atlas of the Absorption of the Atmosphere from 5400 to 8520 Å," *NRL Report 4601* (23Aug1955) (AD71520).
- (267) C. B. Ludwig, W. Malkmus, J. E. Reardon and J. A. L. Thomson, Handbook of Infrared Radiation from Combustion Gases, NASA SP-3080 (1973).
- (268) R. J. Bell, Introductory Fourier Transform Spectroscopy, Academic Press, New York, 1972.
- (269) C. E. Dunning and Fred E. Nicodemus, "Targets," Handbook of Military Infrared Technology, p. 57, Office of Naval Research (1965).
- (270) C. B. Ludwig, M. Griggs, W. Malkmus and E. R. Bartle, "Air Pollution Measurements from Satellites," *NASA CR-2324* (1973).
- (271) M. Griggs, C. G. Ludwig, and M. L. Streiff, Proc. 2nd Int. Clean Air Congress, p 500, Ed. M. M. England and W. T. Beary, Academic Press, N. Y., 1971.
- (272) *Phys. Zeitschrift*, 1, 289 (1900).
- (273) Wolfe, Wm. L., Ed. Handbook of Military Infrared Technology. Office of Naval Research, p. 48 (1965).

References (274) through (288) are not assigned

- (289) 41FR37660, September 7, 1976.
- (290) D. T. Williams and R. N. Hager, Jr., "The Derivative Spectrometer", Applied Optics 9, 1597 (1970).
- (291) J. B. Clements, EPA, Research Triangle Park, North Carolina, phone: (919)541-2196, personal communication.
- (292) H. Segal, "Monitoring Concorde Emissions", J. Air Poll. Contr. Assn., 27, 623, (1977).
- (293) Private Communications, Mr. John Thompkins, FAA, Airways Facility, San Diego, CA (March, 1976).
- (294) J. Reid, B. K. Garside, J. Shewchun, M. El-Sherbiny and E. A. Ballik, "High Sensitivity Point Monitoring of Atmospheric Gases Employing Tunable Diode Lasers," Applied Optics, being published.
- (295) Pollution Equipment News, Vol. 10, No. 3, page 46 (June 1977).
- (296) C. D. Hollowell and R. D. McLaughlin, "Instrumentation for Air Pollution Monitoring Environ. Sci. Techn. f, 1011 (1973).
- (297) "Instrument and Techniques for Exhaust Gas Emissions Measurement", SAE Recommended Practice, J254 (1971).
- (298) "Nondispersive Infrared Analyzer for Specific Gases in Complex Mixtures", NASA TECH BRIEF, Ames Research Center (May 1972).
- (299) Elfers, L. A. Field Operations Guide for Automatic Air Monitoring Equipment, NTIS Report PB 204650, (July 1971).
- (300) Evans, R., EPA-Las Vegas, private communication, 1975.

## REFERENCES

- (301) G. A. Briggs, "Plume Rise," Air Resources Atmospheric Turbulence and Diffusion Laboratory, Environmental Science Services Administration, Oak Ridge, Tennessee, 1969.
- (302) G. A. Briggs, "Plume Rise: A Recent Critical Review," Nuclear Safety, Vol. 12 (No. 1), January-February, 1971, pp. 15-24.
- (303) F. Pasquill, "Atmospheric Diffusion," D. Van Nostrand, New York, 1972.
- (304) O. G. Sutton, "Micrometeorology," McGraw-Hill, New York, 1953.
- (305) D. B. Turner, "Workbook on Atmospheric Dispersion Estimates," U. S. Department of Health, Education, and Welfare, U. S. Public Health Service, Report No. 999-AP-26.
- (306) E. M. Darling, Jr., "Computer Modeling of Transportation-Generated Air Pollution: A State-of-the-Art Survey," U. S. Department of Transportation, Report No. DOT-TSC-OST-72-20, June 1972.
- (307) M. Smith (Editor), "Recommended Guide for the Prediction of the Dispersion of Airborne Effluents," Am. Soc. of Mech. Eng., 1968.
- (308) D. B. Turner, "A Diffusion Model of an Urban Area," Journal of Applied Meteorology, Vol. 3, February 1964, pp. 83-91.
- (309) F. Pasquill, "The Estimation of the Dispersion of Windborne Material," Meteorology Magazine, Vol. 90, 1961, pp. 33-49.
- (310) F. A. Gifford, Jr., "Use of Routine Meteorological Observations for Estimating Atmospheric Dispersion," Nuclear Safety, Vol. 4 (No. 2), July-August 1961, pp. 47-51.
- (311) J. J. Roberts, E. J. Crolse, A. S. Kennedy, J. E. Norco and L. A. Conley, "A Multiple-Source Urban Atmospheric Dispersion Model," Argonne National Laboratory, Report No. ANL/ES-CC-007, May 1970.

- (312) D. M. Rote and L. E. Wangen, "A Generalized Air Quality Assessment Model for Air Force Operations," Air Force Weapons Laboratory, Report No. AFWL-TR-74-304, February 1975.
- (313) D. G. Martin and J. A. Tikvart, "A General Atmospheric Diffusion Model for Estimating the Effects on Air Quality of One or More Sources," Air Pollution Control Association paper, June 1968, pp. 68-148.
- (314) "Air Quality Display Model," TRW Systems, November 1969, NTIS No. PB-189194.
- (315) R. C. Sklarew, A. J. Fabrick, and J. E. Prager, "A Particle-in-Cell Method for Numerical Solution of the Atmospheric Diffusion Equation and Applications to Air Pollution Problems," Systems, Science & Software, Report 3SR-844, Volume 1, November 1971.
- (316) K. L. Calder, "On the Equation of Atmospheric Diffusion," Quarterly J. Royal Meteorological Society, Volume 91, 1965, pp. 514.
- (317) J. M. Haber, "A Survey of Computer Models for Predicting Air Pollution from Airports," J. H. Wiggins Company, Report No. 75-1231-1, May 23, 1975.
- (318) G. C. Holyworth, "Estimates of Mean Maximum Mixing Depths in the Contiguous United States," Monthly Weather Review, Volume 92 (No. 5), May 1964, pp. 235-242.
- (319) J. Z. Holland, "A Meteorological Survey of the Oak Ridge Area," Atomic Energy Commission, Report No. ORO-99, Washington, D.C., 1953, pp. 554-559.
- (320) R. I. Larsen, "A New Mathematical Model of Air Pollution Concentration Averaging Time and Frequency," Journal of the Air Pollution Control Association, Volume 19 (No. 1), January 1969.
- (321) M. Platt, et. al., "The Potential Impact of Aircraft Emissions upon Air Quality," Northern Research and Engineering Corporation, Report No. 1167-1, December 1971.

- (322) M. Platt, et. al., "Assessing the Impact of Aircraft Emissions Upon Air Quality," presented at the 65th Annual Meeting of the Air Pollution Control Association, Miami Beach, Florida, June 18-22, 1972.
- (323) M. Platt and E. K. Bastress, "The Impact of Aircraft Emissions Upon Air Quality," presented at the International Conference on Transportation and the Environment (No. 720610).
- (324) D. O. Martin, "An Urban Diffusion Model for Estimating Long-Term Average Values of Air Quality," Journal of the Air Pollution Control Association, Volume 21 (No. 1), January 1971, pp. 16-19.
- (325) "Nature and Control of Aircraft Engine Exhaust Emissions," Northern Research and Engineering Corporation, Report No. 1134-1, Cambridge, Massachusetts, November 1968.
- (326) S. D. Thayer, "Impact on the Proposed Expansion of the Salt Lake City International Airport on Air Quality," GEOMET Report No. EF-306, March 29, 1974.
- (327) S. D. Thayer, et. al., "Model Verification-Aircraft Emission Impact on Air Quality," GEOMET Report No. EF-262, May 1974.
- (328) S. D. Thayer, "The Development and Validation of an Airport Air Quality Model," Preprint from the Symposium on Atmospheric Diffusion and Air Pollution, Santa Barbara, California, September 9-13, 1974.
- (329) J. E. Norco, et. al., "An Air Pollution Impact Methodology for Airports - Phase I," Argonne National Laboratory, January 1973, NTIS PB-220-987.
- (330) D. M. Rote, et. al., "Airport Vicinity Air Pollution Study," Federal Aviation Administration, Report No. FAA-RR-73-113, December 1973.
- (331) D. M. Rote, et. al., "Airport Vicinity Air Pollution Study - Model Application and Validation and Air Quality Impact Analysis at Washington National Airport," Federal Aviation Administration Report No. FAA-RD-74-132, July 1974.

- (332) R. R. Cirello, et. al., "Airport Vicinity Air Pollution Study: The Impact of Modified Aircraft Taxi Procedures on Airport Air Quality," Federal Aviation Administration Report No. FAA-RD-212, December 1974.
- (333) J. E. Carson and H. Moses, "The Validity of Currently Popular Plume Rise Formulas," in Proceedings USAEC Meteorological Information Meeting, held at Chalk River Nuclear Laboratories, September 11-14, 1967, pp. 1-20.
- (334) I. T. Wang and R. M. Rote, "A Finite Line Source Dispersion Model for Mobile Source Air Pollution," Journal of the Air Pollution Control Association, Volume 25 (No. 7), July 1975, pp. 730-733.
- (335) T. D. Wolsko, M. T. Matthies, and R. E. Wendell, "Transportation Air Pollutant Emissions Handbook," Argonne National Laboratory, Report No. ANL/ES-15, Argonne, Illinois, July 1972.
- (336) D. M. Rote and L. E. Wangen, "A Generalized Air Quality Assessment Model for Air Force Operations," U. S. Air Force Weapons Laboratory, Report No. AFWL-TR-74-304, February 1975.
- (337) "Development of Procedures to Simulate Motor Vehicle Pollution Levels," ERT Document P-343-F, Environmental Research and Technology, Inc., Lexington, Massachusetts.
- (338) B. A. Egan and J. R. Mahoney, "Numerical Modeling of Advection and Diffusion of Urban Area Source Pollutants," J. Applied Meteorology, 1972, pp. 312-332.
- (339) P. B. S. Lissaman, "A Simple Unsteady Concentration Model Explicitly Incorporating Ground Roughness and Heat Flux," APCA Paper 73-219, presented at 66th APCA Meeting, Chicago, Illinois, June 1973.
- (340) P. M. Roth, et. al., "An Examination of the Accuracy and Adequacy of Air Quality and Monitoring Data for Use in Assessing the Impact of EPA Significant Deterioration Regulations on Energy Development," Contract EF 75-58R for American Petroleum Institute, August 1975.

## APPENDICES

- I      (40 CFR 50) National Primary and Secondary Ambient Air Quality Standards
- II     (40 CFR 53) Ambient Air Monitoring Reference and Equivalent Methods
- III    Guideline For Public Reporting of Daily Air Quality
- IV    (40 CFR 87) Control of Air Pollution From Aircraft and Aircraft Engines
- V     Review of Calibration Span Gases
- VI    List of Commercially Available Point Samplers
- VII   Derivation of Signal-To-Noise Ratio Equations and Error Analysis
- VIII   Meteorological Instruments For Use in The Calibration Test Range
- IX    Electromagnetic Interference Characteristics Requirements for Equipment

I a

APPENDIX I

NATIONAL PRIMARY AND SECONDARY  
AMBIENT AIR QUALITY STANDARDS  
(40 CFR 50)

## CHAPTER I—ENVIRONMENTAL PROTECTION AGENCY (Continued)

### SUBCHAPTER C—AIR PROGRAMS

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### SUBCHAPTER C—AIR PROGRAMS

**PART 50—NATIONAL PRIMARY AND SECONDARY AMBIENT AIR QUALITY STANDARDS**

Sec.

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50.2 Scope.

50.3 Reference conditions.

50.4 National primary ambient air quality standards for sulfur oxides (sulfur dioxide).

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50.8 National primary and secondary ambient air quality standards for carbon monoxide.

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**APPENDIX A—Reference Method for the Determination of Sulfur Dioxide in the Atmosphere (Paramoniline Method).**

**APPENDIX B—Reference Method for the Determination of Sulfur Dioxide (High Volume Method).**

**APPENDIX C—Measurement Principle and Calibration Procedure for the Continuous Measurement of Carbon Monoxide in the Atmosphere (Non-Dispersive Infrared Spectrometry).**

**APPENDIX D—Measurement Principle and Calibration Procedure for the Measurement of Photochemical Oxidants Corrected for Interferences due to Nitrogen Oxides and Sulfur Dioxide.**

**APPENDIX E—Reference Method for the Determination of Hydrocarbons Corrected for Methane.**

**APPENDIX F—Reference Method for the Determination of Nitrogen Dioxide (24-Hour Sampling Method).**

**ATTACHMENT:** The provisions of this Part so limited under sec. 4, Public Law 91-604, 84 Stat. 1070 (42 U.S.C. 1857c-4).

**SOURCE:** The provisions of this Part so appear at 3d FR. 222834, Nov. 25, 1971, unless otherwise noted.

### Title 40—Protection of Environment

#### § 50.1 Definitions.

(a) As used in this part, all terms not defined herein shall have the meaning given them by the Act.

(b) "Act" means the Clean Air Act, as amended (42 U.S.C. 1857-1857l, as amended by Pub. L. 91-604).

(c) "Agency" means the Environmental Protection Agency.

(d) "Administrator" means the Administrator of the Environmental Protection Agency.

(e) "Ambient air" means that portion of the atmosphere, external to buildings, to which the general public has access.

(f) "Reference method" means a method of sampling and analyzing the ambient air for any air pollutant that is specified as a reference method in an appendix to this part, or a method that has been designated as a reference method in accordance with Part 53 of this chapter; it does not include a method for which a reference method designation has been cancelled in accordance with § 53.11 or § 53.16 of this chapter.

(g) "Equivalent method" means a method of sampling and analyzing the ambient air for an air pollutant that has been designated as an equivalent method in accordance with Part 53 of this chapter; it does not include a method for which an equivalent method designation has been cancelled in accordance with § 53.11 or § 53.16 of this chapter.

(h) "Reference method" means a method of sampling and analyzing the ambient air for an air pollutant that has been designated as an equivalent method in accordance with Part 53 of this chapter; it does not include a method for which an equivalent method designation has been cancelled in accordance with § 53.11 or § 53.16 of this chapter.

[36 FR 222834, Nov. 25, 1971, as amended at 41 FR 11253, Mar. 17, 1976]

#### § 50.2 Scope.

(a) National primary and secondary ambient air quality standards under section 109 of the Act are set forth in this part.

(b) National primary ambient air quality standards define levels of air quality which the Administrator judges necessary, with an adequate margin of safety, to protect the public health.

National secondary ambient air quality standards define levels of air quality which the Administrator judges necessary, with an adequate margin of safety, to protect the public health.

The national secondary ambient air quality standard for sulfur dioxide measured as sulfur dioxide by the reference method described in Appendix A to this part, or by any equivalent method is 1,300 micrograms per cubic meter (0.14 p.p.m.) maximum 3-hour concentration not to be exceeded more than once per year.

[38 FR 25681, Sept. 14, 1973]

(c) National primary ambient air quality standards for particulate matter.

National primary ambient air quality standards for particulate matter.

National secondary ambient air quality standards for particulate matter.

National primary and secondary ambient air quality standards for sulfur dioxide (sulfur dioxide).

National primary ambient air quality standards for sulfur dioxide (sulfur dioxide).

National secondary ambient air quality standards for sulfur dioxide (sulfur dioxide).

National primary and secondary ambient air quality standards for carbon monoxide.

National primary and secondary ambient air quality standards for photochemical oxidants.

National primary and secondary ambient air quality standard for hydrocarbons.

National primary and secondary ambient air quality standard for nitrogen dioxide.

more stringent than the national standards.

#### § 50.3 Reference conditions.

All measurements of air quality are corrected to a reference temperature of 25° C, and to a reference pressure of 760 millimeters of mercury (10,132 millibars).

The national primary ambient air quality standards as sulfur dioxide by the reference method described in Appendix A to this part, or by an equivalent method,

(a) 80 micrograms per cubic meter (0.03 p.p.m.) annual arithmetic mean.

(b) 365 micrograms per cubic meter (0.14 p.p.m.)—Maximum 24-hour concentration not to be exceeded more than once per year.

The national secondary ambient air quality standard for sulfur dioxide measured as sulfur dioxide by the reference method described in Appendix A to this part, or by any equivalent method is 1,300 micrograms per cubic meter (0.14 p.p.m.) maximum 3-hour concentration not to be exceeded more than once per year.

The national primary ambient air quality standards for particulate matter.

The national primary ambient air quality standards for particulate matter.

The national primary and secondary ambient air quality standards for sulfur dioxide (sulfur dioxide).

The national primary ambient air quality standards for sulfur dioxide (sulfur dioxide).

The national primary and secondary ambient air quality standards for carbon monoxide.

The national primary and secondary ambient air quality standards for photochemical oxidants.

The national primary and secondary ambient air quality standard for hydrocarbons.

The national primary and secondary ambient air quality standard for nitrogen dioxide.

The national primary ambient air quality standards for particulate matter.

The national primary ambient air quality standards for particulate matter.

The national primary and secondary ambient air quality standards for sulfur dioxide (sulfur dioxide).

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The national primary and secondary ambient air quality standards for carbon monoxide.

The national primary and secondary ambient air quality standards for photochemical oxidants.

The national primary and secondary ambient air quality standard for hydrocarbons.

The national primary and secondary ambient air quality standard for nitrogen dioxide.

The national primary ambient air quality standards for particulate matter.

The national primary ambient air quality standards for particulate matter.

The national primary ambient air quality standards for particulate matter.

The national primary ambient air quality standards for particulate matter.

The national primary ambient air quality standards for particulate matter.

## Chapter I—Environmental Protection Agency

### Title 40—Protection of Environment

#### App. A

scribed in Appendix B to this part, or by an equivalent method, are:

(a) .75 micrograms per cubic meter—annual geometric mean.

(b) 260 micrograms per cubic meter—maximum 24-hour concentration not to be exceeded more than once per year.

**§ 50.7 National secondary ambient air quality standards for particulate matter.**

The national secondary ambient air quality standards for particulate matter, measured by the reference method described in Appendix B to this part, or by an equivalent method, are:

(a) .60 micrograms per cubic meter—annual geometric mean, as a sum to be used in assessing implementation plans to achieve the 24-hour standard.

(b) 150 micrograms per cubic meter—maximum 24-hour concentration not to be exceeded more than once per year.

**§ 50.8 National primary and secondary ambient air quality standards for carbon monoxide.**

The national primary and secondary ambient air quality standards for carbon monoxide, measured by a reference method based on Appendix C to this part and designated in accordance with Part 53 of this chapter, or by an equivalent method, are:

(a) 10 milligrams per cubic meter (.9 ppm)—maximum 8-hour concentration not to be exceeded more than once per year.

(b) 40 milligrams per cubic meter (.15 ppm)—maximum 1-hour concentration not to be exceeded more than once per year.

**§ 50.9 National primary and secondary ambient air quality standards for photochemical oxidants.**

The national primary and secondary ambient air quality standard for photochemical oxidants, measured and corrected for interferences due to nitrogen oxides and sulfur dioxide by a reference method based on Appendix D to this part and designated in accordance with Part 53 of this chapter, or by an equivalent method, is: 150 micrograms per cubic meter (.008 ppm), maximum 1-hour

concentration in the range of 50 to 100  $\mu\text{g}/\text{m}^3$ , (0.01 to 0.40 ppm), can be measured under the conditions given. One can measure larger volumes of air, but only if sampling periods up to 24 hours.

**2. Range and Sensitivity.** 2.1 Concentrations of sulfur dioxide in the range of 50 to 100  $\mu\text{g}/\text{m}^3$ , (0.01 to 0.40 ppm), can be measured under the conditions given. One can measure larger volumes of air, but only if the absorption efficiency of the particular system is first determined. Higher concentrations can be analyzed by using smaller 50  $\mu\text{g}/\text{m}^3$  aliquots of the collected sample. Beer's Law is followed through the working range from 0.03 to 1.0 absorption units (0.3 to 0.7  $\mu\text{g}$  of sulfate ion in 25 ml final solution computed as  $\text{SO}_4^{2-}$ ).

2.2 The lower limit of detection of sulfur dioxide in 10 ml TCM is .073  $\mu\text{g}$ , (based on twice the standard deviation) representing a concentration of 25  $\mu\text{g}/\text{m}^3 \text{SO}_4^{2-}$  (0.01 p.p.m.) in an air sample of 30 liters.

(NO FR 22284, Nov. 25, 1971, as amended at 40 FR 2063, Feb. 18, 1975)

15 nm. Reagent blank problems may occur with spectrophotometers having greater spectral band width. The wavelength calibration of the instrument should be verified. If transmittance is measured, this can be converted to absorbance:

$$A = \log_{10}(1/T)$$

#### 6. Reagents.

6.1 Sampling.

6.1.1 Distilled water. Must be free from oxidants.

6.1.2 Absorbing Reagent (0.04 M Potassium Tetraethoxomercurate (TOM)). Dissolve 10.88 g. mercuric chloride (0.008 M EDTA (ethylendiaminetetraacetic acid), disodium salt), and 6.0 g. potassium chloride in water and bring to mix in a 1,000-ml. volumetric flask. (Caution: Highly poisonous. If spilled on skin, flush off with water immediately). The pH of this reagent should be approximately 4.0, but it has been shown that there is no appreciable difference in collection efficiency over the range of pH 6 to pH 3.7. The absorbing reagent is normally stable for 6 months. If a precipitate forms, discard the reagent.

#### 6.2 Analysis.

6.2.1 Sulfuric Acid (0.6 Percent). Dissolve 0.6 g. sulfuric acid in 100 ml. distilled water. Prepare fresh daily.

6.2.2 Formamide (0.2 percent). Dilute 5 ml. formamide solution (36-38 percent) to 1,000 ml. with distilled water. Prepare daily.

6.2.3 Stock Iodine Solution (0.1 N). Place 12.7 g. iodine in a 250-ml. beaker; add 40 g. potassium iodide and 25 ml. water. Stir until all is dissolved, then dilute to 1,000 ml. with distilled water.

6.2.4 Iodine (0.01 N). Prepare approximately 0.01 N iodine solution by diluting 60 ml. of stock solution to 500 ml. with distilled water.

6.2.5 Starch Indicator Solution. Triturate 0.4 g. soluble starch and 0.002 g. mercuric iodide (preservative) with a little water, and add the paste slowly to 200 ml. boiling water. Continue boiling until the solution is clear; cool, and transfer to a glass-stoppered bottle.

6.2.6 Stock Sodium Thiosulfate Solution (0.1 N). Prepare a stock solution by dissolving 25 g. sodium thiosulfate ( $\text{Na}_2\text{S}_2\text{O}_3 \cdot 5\text{H}_2\text{O}$ ) in 1,000 ml. freshly boiled, cooled, distilled water and add 0.1 g. sodium carbonate to the solution. Allow the solution to stand 1 day before standardizing. To standardize, accurately weigh to the nearest 0.1 mg. 1.6 g. primary standard potassium iodate dried at 180°C. and dilute to volume in a 500-ml. volumetric flask. To a 50-ml. iodine flask, pipet 50 ml. of iodate solution. Add 0.2 g. potassium iodide and 10 ml. of 1 N hydrochloric acid. Stopper the flask. After 5 minutes, titrate with stock thiosulfate solution to a pale yellow. Add 6 ml. starch indicator solution and continue the titration until the blue color disappears.

#### 6.3 Apparatus.

6.3.1 Sampler. Absorber normally used in air pollution sampling are acceptable for concentrations above 25-45  $\mu\text{g}/\text{m}^3$ . (0.01 p.p.m.). An All-glass midge impinger, as shown in Figure A1, is recommended for 30-minute and 1-hour samples.

For 24-hour sampling, assemble an absorber following the parts:

Polypropylene 2-port tube closures, special manufacture (available from Bel-Art Products, Pequannock, N.J.).

Glass impingers, 6 mm. tubing, 6 inches long, one end drawn to small diameter such that No. 75 jewelers drill will pass through but No. 78 jewelers drill will not. (Otherwise end is polished.)

Polypropylene tubes, 1/4 by 32 mm. (NaOH or equal).

6.3.2 Pump. Capable of maintaining an air pressure differential greater than 0.7 atm. at the desired flow rate.

6.3.3 Air Floumeter or Critical Orifice. A calibrated rotameter or critical orifice capable of measuring air flow within  $\pm 2$  percent. For 30-minute sampling, a 22-gauge hypodermic needle 1 inch long may be used as a critical orifice to give a flow of about 1 liter/minute. For 1-hour sampling, a 23-gauge hypodermic needle five-eighths of an inch long may be used as a critical orifice to give a flow of about 0.4 liter/minute. For 24-hour sampling, a 27-gauge hypodermic needle three-eighths of an inch long may be used to give a flow of about 0.2 liter/minute. Use a membrane filter to protect the needle (Figure A3).

#### 6.4 Analysis.

6.4.1 Spectrophotometer. Suitable for measurement of absorbance at 568 nm, with an effective spectral band width of less than

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Calculate the normality of the stock thionulfate solution:  

$$N = \frac{W}{M} \times 2.80$$

$$2.80 = \frac{10^4 (\text{concentration of g. to mg.}) \times 0.1}{35.67 (\text{equivalent weight of potassium iodate used})}$$

**4.2.7 Sodium Thionulfate Titrant (0.01 N).** Dissolve 100 ml. of the stock thionulfate solution in 1,000 ml. of freshly boiled distilled water.

Normality = Normality of stock solution  
 $\times 0.100.$

**4.2.8 Standardized Sulfitite Solution for Preparing Working Sulfitite-TCM Solution.** Dissolve 0.3 g. sodium metabisulfite ( $\text{Na}_2\text{S}_2\text{O}_5$ ) or 0.40 g. sodium sulfite ( $\text{Na}_2\text{SO}_3$ ) in 500 ml. of recently boiled, cooled, distilled water. (Sulfitite solution is unstable; it is therefore important to use water of the highest purity to minimize this instability.) This solution contains the equivalent of 320 to 400  $\text{mg./ml.}$  of  $\text{SO}_3^{2-}$ . The actual concentration of the solution is determined by adding excess iodine and back-titration with standard sodium thionulfate solution. To back-titrate, pipet 50 ml. of the 0.01 N iodine into each of two 500-ml. Erlenmeyer flasks (A and B). To flask A (blank) add 25 ml. distilled water and to flask B (sample) pipet 20 ml. sulfur solution, stopper the flasks and allow to react for 5 minutes. Prepare the working sulfitite-TCM solution (4.2.9) at the same time (tincture solution is added to the flasks). By means of a buret containing standardized 0.01 N thiosulfate, titrate each flask in turn to a pale yellow. Then add 5 ml. starch solution and distilled water. This reagent is stable for at least 9 months.

**4.2.9 Working Sulfitite-TCM Solution.** Pipet accurately 2 ml. of the standard solution into a 100 ml. volumetric flask and bring to mark with 0.04 M TCM. Calculate the concentration of sulfur dioxide in the working solution:

$$\text{mg. } \text{SO}_3^{2-}/\text{ml.} = \frac{(A - B)}{26} (N) (32.000) \times 0.02$$

A = Volume thionulfate for blank, ml.  
 B = Volume thionulfate for sample, ml.  
 N = Normality of thionulfate titrant.

26 = Milliequivalents wt. of  $\text{SO}_3^{2-}$ .  
 32.000 = Volume standard sulfite solution.

0.02 = Dilution factor.

This solution is stable for 30 days if kept at  $5^\circ\text{C}$ . (refrigerator.) If not kept at  $5^\circ\text{C}$ , prepare daily.

**4.2.10 Purified Pararoniline Stock Solution (0.2 Percent Nominal).** The pararoniline dye must meet the following performance specifications: (1) the dye must

sampled by multiplying the flow rate by the time in minutes and record the atmospheric pressure and temperature. Remove and stopper the impinger. If the sample is stored for more than a day before analysis, keep it at  $5^\circ\text{C}$ . In a refrigerator (see 4.2), keep the sample at  $5^\circ\text{C}$ .

**7.1.2 24-Hour Sampling.** Place 50 ml. TCM solution in a large absorber and collect the sample at 0.2 liter/minute for 24 hours from midnight to midnight. Make sure no entrainment of solution results with the impinger. During collection and storage protect from direct sunlight. Determine the total air volume by multiplying the air flow rate by the time in minutes. The correction of 24-hour measurements for temperature and pressure is extremely difficult and is not ordinarily done. However, the accuracy of the measurements will be improved if atmospheric corrections can be applied. If storage is necessary, refrigerate at  $5^\circ\text{C}$ . (see 4.2).

**7.2 Sample Preparation. After collection, if a precipitate is observed in the sample, remove it by centrifugation.**

**7.2.1 30-Minute and 1-Hour Samples.** Transfer the sample quantitatively to a 25-ml. volumetric flask; use about 5 ml. distilled water for rinsing. Delay analyses for 20 minutes to allow any ozone to decompose.

**7.2.1.2 24-Hour Sample.** Dilute the entire sample to 50 ml. with absorbing solution. Pipet 6 ml. of the sample into a 25-ml. volumetric flask for chemical analyses. Bring volume to 10 ml. with absorbing reagent. Delay analyses for 20 minutes to allow any ozone to decompose.

**7.2.2 Determination.** For each set of determinations prepare a reagent blank by adding 10 ml. unspiked TCM solution to a 25-ml. volumetric flask. Prepare a control solution by adding 2 ml. of working sulfitite-TCM solution and 8 ml. TCM solution to a 25-ml. volumetric flask. To each flask containing either sample, control solution, or reagent blank, add 1 ml. 0.6 percent sulfite acid and allow to react 10 minutes to destroy the nitrite from excess of nitrosodimethylhydride solution. Then 6 ml. portions of aminesolution. Start a laboratory timer that has been set for 30 minutes. Bring all flasks to volume with freshly boiled and cooled distilled water and mix thoroughly. After 30 minutes and before 60 minutes, determine the absorbances of the sample (denote as A), reagent blank (denote as B), and the control solution at 548 nm, using 1-cm. optical path length cells. Use distilled water, not the reagent blank, as the reference.

(Note) This is important because of the color sensitivity of the reagent blank to temperature changes which can be induced in the cell compartment of a spectrophotometer.

**7.3 Procedure with  $\text{SO}_2$  Permeation Tubes.**

**8.2.1 General Considerations.** Atmospheres containing accurately known amounts of sulfur dioxide at levels of interest can be

in the absorbance cells, because a film of dye may be deposited. Clean cells with alcohol after use. If the temperature of the determinations does not differ by more than  $2^\circ\text{C}$ , the reagent blank should be within 0.03 absorbance units of the Y-intercept of the calibration curve (4.2). If the reagent blank differs by more than 0.03 absorbance unit from that found in the calibration curve, prepare a new curve.

**7.2.3 Absorbance Range.** If the absorbance of the sample solution ranges between 1.0 and 2.0, the sample can be diluted 1:1 with a portion of the reagent blank and read within a few minutes. Solutions with higher absorbance should be diluted up to 10-fold with the reagent blank in order to obtain accurate readings within 10 percent of the true absorbance value.

**8 Calibration and Efficiency.**

Calibrate flormeters and hydrometer needles (8) against a calibrated wet test meter.

**8.2 Calibration Curves.**

**8.2.1 Procedure with Sulfitite Solution.** Accurately pipet graduated amounts of the working sulfitite-TCM solution (4.2.9) (such as 0, 0.5, 1, 2, 3, and 4 ml.) into a series of 25-ml. volumetric flasks. Add sufficient TCM solution to each flask to bring the volume to approximately 10 ml. Then add the remaining reagents as described in 7.2.2. For maximum precision use a constant-temperature bath.

The temperature of calibration should be maintained within  $\pm 1^\circ\text{C}$ . and the temperature of calibration and the temperature of analysis must be within 2 degrees. Plot the absorbance against the total concentration of  $\text{SO}_3^{2-}$  for the corresponding solution. The total  $\text{mg. SO}_3^{2-}$  in the corresponding solution equals the concentration of the standard (Section 6.2.9) in  $\text{mg. SO}_3^{2-}/\text{ml.}$  times the ml. of the solution added (mg.  $\text{SO}_3^{2-}$ /ml.  $\times 10^6 \times V$  ml. added). A linear relationship should be obtained and the Y-intercept should be within 0.03 absorbance units of the zero standard absorbance. For maximum precision determine the line of best fit using the method of least squares. Determine the slope of the line of best fit, calculate its reciprocal and denote as B. B is the calibration factor. (See Section 6.2.10.1 for specifications on the slope of the calibration curve.) This calibration factor can be used for calculating results provided there are no radical changes in temperature or pH. At least one control sample containing a known concentration of  $\text{SO}_3^{2-}$  for each series of determinations, is recommended to insure the reliability of this factor.

**8.2.2 Procedure with  $\text{SO}_2$  Permeation Tubes.**

**8.2.2.1 General Considerations.** Atmospheres containing accurately known amounts

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prepared using permeation tubes. In the system for generating these atmospheres, the permeation tube rate equals  $\text{SO}_2$  gas at a known, low, constant rate, provided the temperature of the tube is held constant ( $\pm 0.1^\circ\text{C}$ ) and provided the tube has been accurately calibrated at the temperature of use. The  $\text{SO}_2$  gas permeating from the tube is carried by a flow of inert gas to a mixing chamber where it is accurately diluted with  $\text{SO}_2$ -free air to the level of interest and the sample taken. These systems are shown schematically in Figures A2 and A3 and have been described in detail by O'Keefe and Ortman (9), Scaringelli, Frey, and Saltzman (10), and Scaringelli, O'Keefe, Roseberg, and Bell (11).

**8.2.2 Preparation of Standard Atmospheres.** Permeation tube may be prepared or purchased. Scaringelli, O'Keefe, Roseberg, and Bell (11) give detailed, explicit directions for permeation tube calibration. Tubes with a certified permeation rate are available from the National Bureau of Standards. Tube permeation rates from 0 to 0.4 mg./minute, inert gas flows of about 50 ml./minute, and dilution air flow rates from 1.1 to 15 liters/minute conveniently give standard atmospheres containing desired levels of  $\text{SO}_2$  (25 to 390  $\mu\text{g}/\text{m}^3$ ; 0.01 to 0.15 ppm.  $\text{SO}_2$ ). The concentration of  $\text{SO}_2$  in any standard atmosphere can be calculated as follows:

$$C = \frac{P \times 10^6}{B_1 + B_2},$$

Where:

$$C = \text{Concentration of } \text{SO}_2, \mu\text{g}/\text{m}^3, \text{ at reference conditions.}$$

P = Tube permeation rate,  $\mu\text{g}/\text{m}^3/\text{minute}$ .

B<sub>1</sub> = Flow rate of dilution air, liter/minute

B<sub>2</sub> = Flow rate of inert gas, liter/minutes at reference conditions.

**8.2.3 Sampling and Preparation of Calibration Curve.** Prepare a series (usually 10) of standard atmospheres containing  $\text{SO}_2$  levels from 25 to 390  $\mu\text{g}/\text{m}^3$ . Sample each atmosphere using similar apparatus and taking exactly the same air volume as will be done in atmospheric sampling. Determine absorbances as directed in 2. Plot the concentration of  $\text{SO}_2$  in  $\mu\text{g}/\text{m}^3$  (x-axis) against  $A - A_0$  values (y-axis). Draw the straight line of best fit and determine the slope. Alternatively, regression analysis by the method of least squares may be used to calculate the slope. Calculate the reciprocal of the slope and denote as B<sub>r</sub>.

**8.3 Sampling Efficiency.** Collection efficiency is above 98 percent; efficiency may fall off, however, at concentrations below 25  $\mu\text{g}/\text{m}^3$ . (12, 13)

**8.4 Calculations.**

8.4.1 Conversion of Volume. Convert the volume of air sampled to the volume at reference conditions of 25° C. and 760 mm. Hg. (14)

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(On 24-hour samples, this may not be possible.)

$$V_a = \frac{V_p \times P}{P_0 \times 10^6} \times \frac{258}{4 + 273}$$

V<sub>a</sub> = Volume of air at 25° C. and 760 mm. Hg. liters.

V<sub>p</sub> = Volume of air sampled liters.

P = Barometric pressure mm. Hg.

T = Temperature of air sample, °C.

9.2 Sulfur Dioxide Concentration.

9.2.1 When sulfite solutions are used to prepare calibration curves, compute the concentration of sulfur dioxide in the sample:

$$A_2, \mu\text{g}/\text{m}^3 = \frac{(A - A_0)}{V_a} \times D$$

A = Sample absorbance.

A<sub>0</sub> = Reagent blank absorbance.

D = Conversion of blank to cuvette meters.

V<sub>a</sub> = The sample corrected to 25° C. and 760 mm. Hg. liters.

B<sub>r</sub> = Calibration factor,  $\mu\text{g}/\text{absorbance}$

D = Dilution factor.

For 30-minute and 1-hour samples,  
D = 1.  
For 24-hour samples, D = 10.

9.2.2 When  $\text{SO}_2$  gas standard atmospheres are used to prepare calibration curves, compute the sulfur dioxide in the sample by the following formula:

$$B_{SO_2} = \frac{A - A_0}{B_1 + B_2} = (A - A_0) \times B_r$$

A = Sample absorbance.

A<sub>0</sub> = Reagent blank absorbance.

B<sub>1</sub> = (See 8.2.3).

9.2.3 Conversion of  $\mu\text{g}/\text{m}^3$  to  $\mu\text{ppm}$ . If desired, the concentration of sulfur dioxide may be calculated as  $\mu\text{ppm } \text{SO}_2$  at reference conditions as follows:

$$\mu\text{ppm. } \text{SO}_2 = \frac{A - A_0}{B_1 + B_2} \times 3.82 \times 10^{-4}$$

10. References.

- (1) West, P. W., and Gieseke, O. C., "Titration of Sulfur Dioxide as Sulfonate III and Subsequent Colorimetric Determination", Anal. Chem., 28, 1818 (1956).
- (2) Ephraim, P., "Inorganic Chemistry," P. 532, Edited by P. C. L. Thorne and E. R. Roberts, 5th Edition, Longmans, (1948).
- (3) Lykes, O. R., Dowling, P. B., and Blanchard, V. J., "Quantitative Determination of Formaldehyde in Parts Per Hundred Million Concentration Levels", J. Air Poll. Cont. Assoc., 15, 106 (1965).
- (4) Scaringelli, P. P., Saltzman, B. E., and Frey, S. A., "Spectrophotometric Determination of Atmospheric Sulfur Dioxide", Anal. Chem., 39, 1709 (1967).

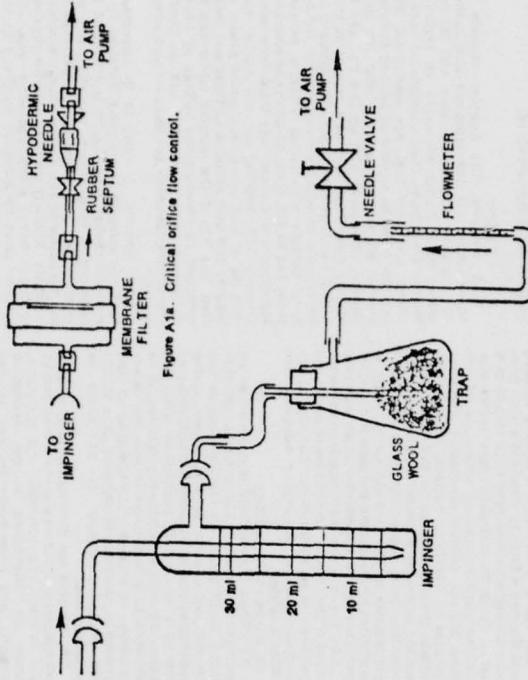


Figure A16. Critical orifice flow control.

Figure A1. Sampling train.

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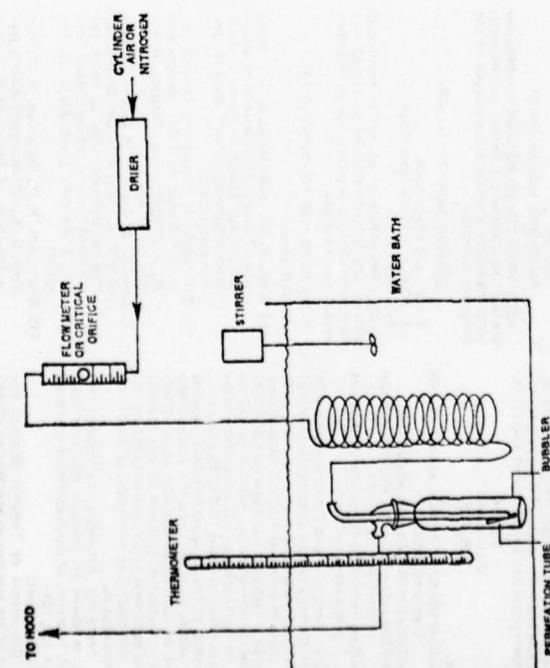


Figure A2. Apparatus for gravimetric calibration and field use.

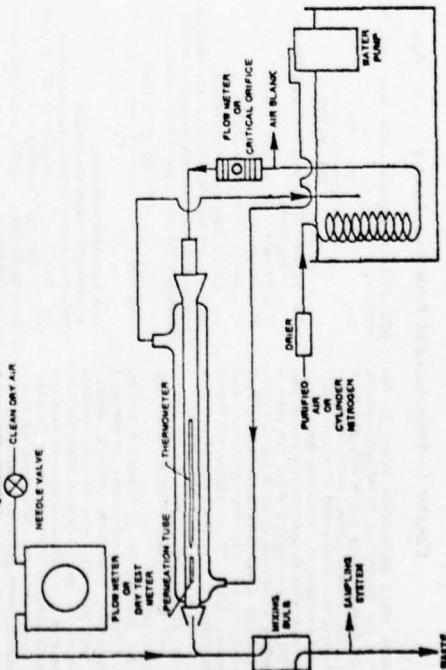


Figure A3. Permeation tube schematic for inventory use.

**APPENDIX B—REFERENCE METHOD FOR THE DETERMINATION OF SUSPENDED PARTICULATES IN THE ATMOSPHERE (BLow VOLUME METHOD)**

#### 1. Principle and Applicability.

1.1 Air is drawn into a covered housing and through a filter by means of a high-slow-rate blower at a slow rate (1.13 to 1.70 mm.<sup>3</sup>/min. to 60 ft./min.) that allows suspended particles having diameters of less than 100  $\mu$ m. (Stokes equivalent diameter) to pass to the filter surface. (1) Particles within the size range of 100 to 0.1  $\mu$ m. diameter are ordinarily collected on glass fiber filters. The mass concentration of suspended particulates in the ambient air ( $\text{mg}/\text{m}^3$ ) is computed by measuring the mass of collected particulates and the volume of air sampled.

1.2 This method is applicable to measurements of the mass concentration of suspended particulates in ambient air. The size of the sample collected is usually adequate for other analyses.

#### 2. Range and Sensitivity.

2.1 When the sampler is operated at an average flow rate of 1.70 m./min. (60 ft./min.) for 24 hours, an adequate sample will be obtained even in an atmosphere having concentrations of suspended particulates as low as 1  $\text{mg}/\text{m}^3$ . If particulate levels are unusually high, a satisfactory sample may be obtained in 6 to 8 hours or less. For determination of average concentrations of suspended particulates in ambient air, a standard sampling period of 24 hours is recommended.

2.2 Weights are determined to the nearest milligram, airflow rates are determined to the nearest: 0.05 m./min. (1.0 ft./min.), times are determined to the nearest 2 minutes, and mass concentrations are reported to the nearest microgram per cubic meter.

#### 3. Inferences.

3.1 Particulate matter that is oily, such as photochemical smog or wood smoke, may block the filter and cause a rapid drop in airflow at a nonuniform rate. Dense fog or high humidity can cause the filter to become too wet and severely reduce the airflow through the filter.

3.2 Glass-fiber filters are comparatively inert to changes in relative humidity. But collected particulates can be hygroscopic. (2)

#### 4. Precision, Accuracy, and Stability.

4.1 Based upon collaborative testing, the relative standard deviation (coefficient of variation) for single analyst variation (reproducibility of the method) is 2.0 percent. The corresponding value for multilaboratory variation (reproducibility of the method) is 3.7 percent. (1)

4.2 The accuracy with which the sampler measures the true average concentration depends upon the constancy of the airflow rate through the sampler. The airflow rate is affected by the concentration and the nature of the dust in the atmosphere. Under these

conditions the error in the measured average concentration may be in excess of  $\pm 50$  percent of the true average concentration, depending on the amount of reduction of airflow rate and on the variation of the mass concentration during the time during the 24-hour sampling period. (4)

#### 5. Apparatus.

5.1 Sampler. The sampler consists of three units: (1) the filter adapter assembly, and (3) the motor unit. Figure B1 shows an exploded view of these parts, their relationship to each other, and how they are assembled. The sampler must be capable of passing environmental air through a 40.5 cm.<sup>2</sup> (63 in.<sup>2</sup>) portion of a clean 20.3 (25.4 cm. (6-1/2 in.) 1.70 m./min. glass-fiber filter at a rate of at least 1.70 m./min. (60 ft./min.). The motor must be capable of continuous operation for 24-hour periods with input voltages ranging from 110 to 120 volts, 60-60 cycles alternating current and must have third-wire safety ground. The housing for the motor unit may be of any convenient construction so long as the unit remains airtight and leak-free. The life of the sampler motor can be extended by lowering the voltage by about 10 percent with a small "Duck or" transformer between the sampler and power outlet.

5.1.2 Sampler Shelter. It is important that the sampler be properly installed in a suitable shelter. The shelter is subjected to extremes of temperature, humidity, and all types of air pollutants. For these reasons the materials of the shelter must be chosen carefully. Properly painted exterior plywood or heavy gauge aluminum serve well. The sampler must be mounted vertically in the shelter so that the glass-fiber filter is parallel with the ground. The shelter must be provided with a door so that the filter is protected from precipitation and debris. The internal arrangement and configuration of a suitable shelter with a gable roof are shown in Figure B2. The clearance area between the main housing and the roof at its closest point should be  $0.90 \pm 0.03$  cm.<sup>2</sup> (90  $\pm$  30 in.<sup>2</sup>), with dimensions of about 26 by 86 cm. (11½ by 14 in.).

5.1.3 Rotameter. Marked in arbitrary units, frequently 0 to 70, and capable of being calibrated. Other devices of at least comparable accuracy may be used.

5.1.4 Orifice Calibration Unit. Consisting of a metal tube 7.6 cm. (3½ in.) ID and 16.3 cm. (6½ in.) long with a static pressure tap 6.1 cm. (2 in.) from one end. See Figure B3. The tube end nearest the pressure tap is flanged to about 10.8 cm. (4½ in.) OD with a male thread of the same size as the inlet end of the high-volume air sampler. A single metal plate 9.2 cm. (3½ in.) in diameter and 0.24 cm. (16 in.) thick with a central orifice 2.9 cm. (1½ in.) in diameter is held in place at the air inlet end with a female threaded ring. The other end of the tube is flanged to

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**6.** minutes, connect the rotameter to the nipple on the back of the sampler, and read the rotameter until with a caliper in a vertical position. Estimate to the nearest whole number. If the ball is fluctuating rapidly, tip the rotameter and slowly straighten it until the ball gives a constant reading. Disconnect the rotameter from the filter assembly and the initial rotameter reading, and record the initial rotameter reading and the starting time and date on the filter folder. The rotameter should never be connected to the sampler every 1/2 hour to be measured.) Sample for 1/2 hour from mid-night to mid-morning and take a final rotameter reading. Record the final rotameter reading and ending time and date on the filter folder. Remove the faceplate as described above and carefully remove the filter from the holder, touching only the outer edges. Fold the filter lengthwise so that only surfaces with localized particulates are in contact, and place in a manila folder. Record on the folder the filter number, location, and any other factors such as meteorological conditions or reading of nearby buildings, that might affect the results. If the sample is defective, void it at this time. In order to obtain a valid sample, the high-volume sampler must be operated with the same rotameter and tuning that were used during its calibration.

**6.2.3** Light Source. Frequency a table of the type used to view X-ray films. **6.2.4** Numbering Device. Equipped with a working chamber designed to handle samples folded 203 by 254 cm. (8 by 10-in.) filters and having a sensitivity of 0.1 mg.

**6.2.5** Industrial Balance. Equipped with a weighing chamber designed to handle samples folded 203 by 254 cm. (8 by 10-in.) filters and having a sensitivity of at least 99 percent.

**6.2.6** Rengents. Glass-fiber filters having a collection efficiency of at least 99 percent for particles of 0.3 micrometer, as measured by the DOP test, are suitable for quantitative measurement of concentrations of suspended particulates. Although some other medium, such as paper, may be desirable for some analyses, if more detailed analysis is contemplated care must be exercised to use filters that contain low background concentrations of the pollutant being investigated. Careful quality control is required to determine background values of these pollutants.

**7. Procedure.**

**7.1** Sampling. Prepare each filter to its light source and insert for pinholes, particles, or other imperfections. Filters with variable imperfections should not be used. A small brush is useful for removing particles. Equilibrate the filters in the filter conditioning environment for 24 hours. Weigh the filters to the nearest milligram; record tare weight and filter identification number. Do not bend or fold the filter before collection of the sample.

**7.1.2** Sample Collection. Open the shelter.

Loosen the wing nuts and remove the faceplate from the filter holder. Install a numbed, powdered, glass-fiber filter in position (ring, etc up), replace the faceplate and fasten securely. Unscrewing will damage the sponge-rubber faceplate gasket. A very light application of talcum powder may be used on the sponge-rubber faceplate gasket to prevent the filter from sticking. During inclement weather the sampler may be removed to a protected area for filter change. Close the filter unit.

The filter unit is held in a vertical position.

Turn the filter unit clockwise.

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### App. B

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(a)(1). This modification consists of an exhaust orifice meter assembly connected through a transducer to a system for continuously recording airflow on a circular chart. The volume of air sampled is calculated by the following equation:

$$V = Q \times T.$$

T = Sampling time, minutes.

The average sampling rate,  $Q$ , is determined from the recorder chart by estimating the flow rate does not vary more than 0.1 m/min. (4 ft/min.) during the sampling period.

If the flow rate does vary more than 0.1 m.<sup>3</sup>/min. (4 ft/min.) during the sampling period, read the flow rate from the chart at 2-hour intervals and take the average.

B. Pressure and Temperature Corrections. If the pressure or temperature during high-volume sampler calibration is substantially different from the pressure or temperature during orifice calibration, a correction of the flow rate,  $Q$ , may be required. If the pressures differ by no more than 15 percent and the temperatures differ by no more than 100 percent ( $^{\circ}$ C), the error in the un-

corrected flow rate will be no more than 15 percent. If necessary, obtain the corrected flow rate as directed below. This correction applies only to orifice meters having a constant orifice coefficient. The coefficient for the calibrating orifice described in 1.4 has been shown experimentally to be constant over the normal operating range of the high-volume sampler (0.6 to 2.4 m.<sup>3</sup>/min.; 30 to 78 ft.<sup>3</sup>/min.). Calculate corrected flow rate:

$$Q_c = Q_i \left[ \frac{T_{i,p}}{T_{c,p}} \right]^{1/4}$$

$Q_c$  = Corrected flow rate, m.<sup>3</sup>/min.

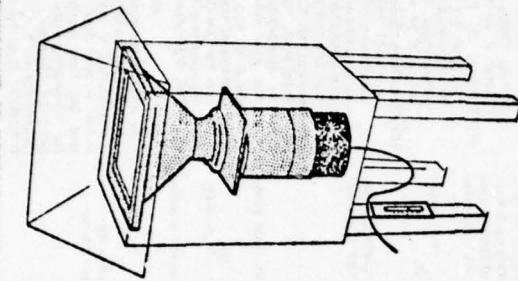
$Q_i$  = Flow rate during high-volume sampler calibration (Section 8.1.2), m.<sup>3</sup>/min.

$T_i$  = Absolute temperature during orifice unit calibration (Section 8.1.1),  $^{\circ}$ K or  $^{\circ}$ R.

$P_i$  = Barometric pressure during orifice unit calibration (Section 8.1.1), mm. Hg.

$T_c$  = Absolute temperature during high-volume sampler calibration (Section 8.1.2),  $^{\circ}$ K or  $^{\circ}$ R.

$P_c$  = Barometric pressure during high-volume sampler calibration (Section 8.1.2), mm. Hg.



I h

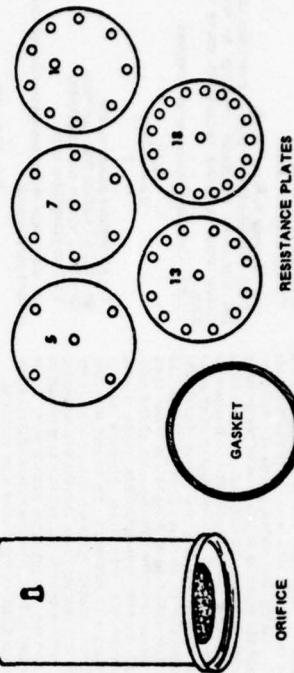


Figure B2. Assembled sampler and shelter.

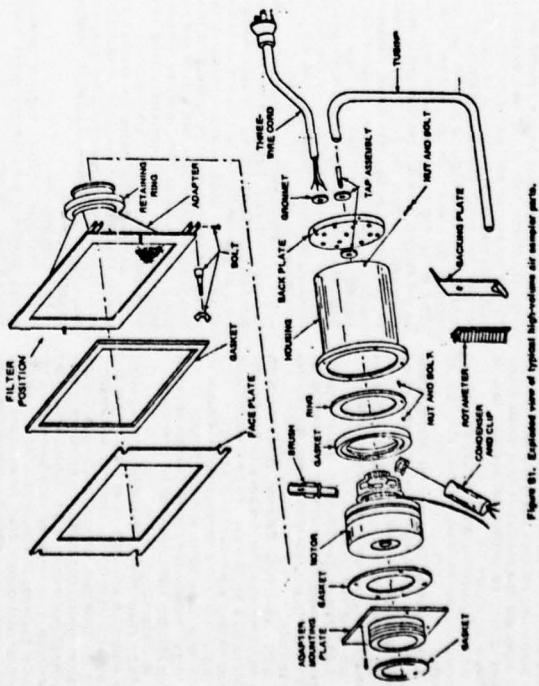


Figure B3. Exploded view of typical high-volume air sampler parts.

Figure B3. Orifice calibration unit.

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### App. D

**APPENDIX C—MEASUREMENT PRINCIPLE AND CALIBRATION PROCEDURE FOR THE CONTINUOUS MEASUREMENT OF CARBON MONOXIDE IN THE ATACORTECH (NON-DISPLACEMENT) SPECTROSCOPE**

1. Principle and applicability  
 1.1 This principle is based on the absorption of infrared radiation by carbon monoxide in a non-dispersive photometer. Both beams pass into matched cells, each containing a selective detector and CO. The CO in the cells absorb infrared radiation only at its characteristic frequencies and the detector is sensitive to those frequencies. With a non-absorbing gas in the reference cell, and with no CO in the sample cell, the signals from both detectors are balanced electronically. Any CO introduced into the sample cell will absorb radiation, which reduces the temperature and pressure in the detector cell and displaces a diaphragm. This displacement is detected electronically and amplified to provide an output signal.

1.2 An analyzer based on this principle will be considered a reference method only if it has been designated as a reference method in accordance with Part 55 of this chapter.

2.—6. [Reserved]

7. Procedure  
 7.1 Calibrate the instrument as described in A.I. 2.1. Gas (sample, zero, calibration, and span) must be introduced into the analytical system. Figure C1 shows a typical flow diagram. For specific operating instructions, refer to the manufacturer's manual.

8. Calibration  
 8.1 Calibration Curve. Determine the linearity of the detector response at the operating flow rate and temperature. Prepare a calibration curve and check the curve furnished with the instrument. Introduce zero gas and set the zero control to indicate a recorder reading of zero. Introduce span gas and adjust the span control to indicate the proper value on the recorder scale (e.g., on 0.56 mg./m.<sup>3</sup> scale, set the 48 mg./m.<sup>3</sup> standard at 50 percent of the recorder chart). Recheck zero and span until adjustments are no longer necessary. Introduce intermediate calibration gases and plot the values obtained. If a smooth curve is not obtained, calibration gases may need replacement.

8.2 Calibration. From the concentrations directly from the calibration curve. No calculations are necessary.

8.3 Carbon monoxide concentrations in mg./m.<sup>3</sup> are converted to pp.m. as follows:

$$\text{pp.m.} = \text{CO} \times 10^6 / 233$$

9.2 Photometry. The Infracord NDIR-CO Analyzer by Frank McElroy, presented at the 11th Methods Conference in Air Pollution, University of California, Berkeley, Calif., April 1, 1970.

10. Bibliography.

Jacobs, M. R. et al., J.A.P.C.A., 9, No. 2, 110-114, August 1969.

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Normality $\text{As}_2\text{O}_3 \times \text{Normality } \text{As}_2\text{O}_5$	Normality $\text{I}_2 =$
6.3 Cylinder Air. Dry grade.	6.9 Diluted Standard Iodine. Immediately before use, pipet 1 ml. standard iodine solution into a 100-ml. volumetric flask and dilute to volume with absorbing reagent.
6.4 Activated Charcoal Trap. For filtering cylinder air.	7. Procedure
6.5 Purified Water. Used for all reagents. To distilled or deionized water in an all-glass distillation apparatus, add a crystal of potassium permanganate and a crystal of barium hydroxide, and boil.	7.1 Instruments can be constructed from this components given here or may be purchased. If commercial instruments are used, follow the specific instructions given in the manufacturer's manual. Calibrate the instruments into the system under the same conditions as directed in section 8. Introduce samples into the system. By proper adjustments of zero and span controls, direct reading of ozone concentration is possible.
6.6 Absorbing Reagent. Dissolve 13.6 g. potassium dibydrogen phosphate ( $\text{K}_2\text{HPO}_4$ ), 14.2 g. anhydrous diiodum hydrogen phosphate ( $\text{Na}_2\text{HPO}_4 \cdot 12\text{H}_2\text{O}$ ), and 10.0 g. potassium iodide ( $\text{KI}$ ) in purified water and dilute to 1,000 ml. The pH should be $6.8 \pm 0.2$ . The solution is stabilized for several weeks if stored in a glass-stoppered amber bottle in a cool, dark place.	7.2 Calibration. Prepare a curve of absorbance of various iodine solutions against calculated ozone equivalents as follows:
6.7 Standard Arsenous Oxide Solution (0.25 N). Use primary standard grade arsenious oxide ( $\text{As}_2\text{O}_3$ ). Dry 1 hour at 105° C. immediately before using. Accurately weigh, to the nearest 0.1 mg., 24.6 arsenious oxide from a small glass-stoppered weighing bottle. Dissolve in 25 ml. 1 N sodium hydroxide in a flask or beaker on a steam bath. Add 26 ml. 1 N sulfuric acid. Cool, transfer quantitatively to a 1,000-ml. volumetric flask, and dilute to volume. Note: Solution must be neutral to litmus, not alkaline.	7.3 Calibration Curves. Prepare a curve of absorbance versus total $\text{As}_2\text{O}_3$ .
6.8 Standard Arsenous Oxide ( $\text{As}_2\text{O}_3$ )	7.4 Calibration. Total $\text{As}_2\text{O}_3 = (\text{N}/(96))V$ . $V = \text{Volume of diluted standard I}_2 \text{ added, ml.}$ $N = \text{Normality of diluted standard I}_2 \text{ added, ml.}$ $V = 1/2 \text{ Volume of diluted standard I}_2 \text{ added, ml.}$
6.9 Stereob. Indicator. Solution (0.2 percent). Titrimate 0.4 g. soluble starch and approximately 2 mg. mercurio iodide (preservative) with a little water. Add the paste slowly to 300 ml. of boiling water. Continue boiling until the solution is clear, allow to cool, and transfer to a glass-stoppered bottle.	8.1 Instrument Calibration. Assemble the apparatus as shown in Figure D3. The ozone concentration produced by the generator may be varied by changing the position of the adjustable sleeve. For calibration of ambient air analyzer, the ozone source should be capable of producing ozone concentrations in the range 100 to 1,000 pp.m. (0.06 to 0.6 pp.m.) at a flow rate of at least 6 liters per minute. At all times the air flowing through the generator must be greater than the total flow required by the sampling system.
6.10 Standard Iodine Solution (0.05 N).	8.2 Sampling and Analysis of Test Atmospheres. Assemble the KI sampling train as shown in Figure D4. Use ground-plane connections upstream from the impinger. Butt-to-butt connections with Tygon tubing may be used. The manifold distributing the test atmosphere must be sampled simultaneously by the KI sampling train and the instrument to be calibrated. Check assembly systems for leaks. Record the instrument response in nanoseconds at each concentration (usually air). Establish these concentrations by analysis, using the new
6.11 Preparation. Dissolve 6.0 g. potassium iodide (KI) and 1.8 g. remelted iodine (I <sub>2</sub> ) in 10 ml. purified water. When the iodine dissolves, transfer the solution to a 500-ml. glass-stoppered volumetric flask. Dilute to mark with purified water and mix thoroughly. Keep solution in a dark brown glass-stoppered bottle away from light, and store as necessary.	8.3 Standardization. Pipet accurately 20 ml. standard arsenous oxide solution into a 300-ml. Erlenmeyer flask. Add about 2 g. sodium bicarbonate, and add about 2 ml. water.
6.12 Standardization. Pipet accurately 20 ml. standard arsenous oxide solution into a 300-ml. Erlenmeyer flask. Add about 2 g. sodium bicarbonate, and add about 2 ml. water.	8.4 Titration. Thoroughly mix the standard solution with the standard iodine solution using 6 ml. starch solution as indicator. Saturate the solution with carbon dioxide near the end point by adding 1 ml. of 1:10 sulfuric acid. Continue the titration to the first appearance of a blue color which persists for 30 seconds.

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Calculate ozone concentration in p.p.m. as follows:

$$p.p.m. O_3 = \frac{P_E - P_0}{V_a} \times 8.10 \times 10^{-4}$$

**8.2.1** Blank. With ozone lamp off, flush the system for several minutes to remove residual ozone. Pipe 10 ml. absorbent reagent into each absorber. Draw air from the ozone-generating system through the sampling train at 0.2 to 1 liter/minute for 10 minutes. Immediately transfer the exposed solution to a clean 1-cm. cell. Determine the absorbance at 332 nm. against unexposed absorbing reagent as the reference. If the system blank gives an absorbance, continue flushing the ozone generation system until no absorbance is obtained.

**8.2.2** Test 4 mm<sup>2</sup>/cm<sup>3</sup>. With the ozone lamp operating, equilibrate the system for about 10 minutes. Pipe 10 ml. of absorbing reagent into each absorber and collect samples for 10 minutes in the concentration range desired for calibration. Immediately transfer the solutions from the two absorbers to clean 1-cm. cells. Determine the absorbance of each at 332 nm. Against unexposed absorbing reagent as the reference. Add the absorbances of the two solutions to obtain total absorbance. Read total O<sub>3</sub> from the calibration curve (see 8.1). Calculate total volume of air sampled corrected to reference conditions of 25° C. and 160 mm. Hg. as follows:

$$V_a = V \times \frac{P}{P_0} \times \frac{298}{273} \times 10^{-4}$$

V<sub>a</sub> = Volume of air at reference conditions, m<sup>3</sup>  
 V = Volume of air at sampling conditions, liters.  
 P = Barometric pressure at sampling conditions, mm. Hg.  
 P<sub>0</sub> = Temperature at sampling conditions, °C.  
 10<sup>-4</sup> = Conversion of liters to m<sup>3</sup>.

## Figure 40—Protection of Environment

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### SAMPLE AIR IN

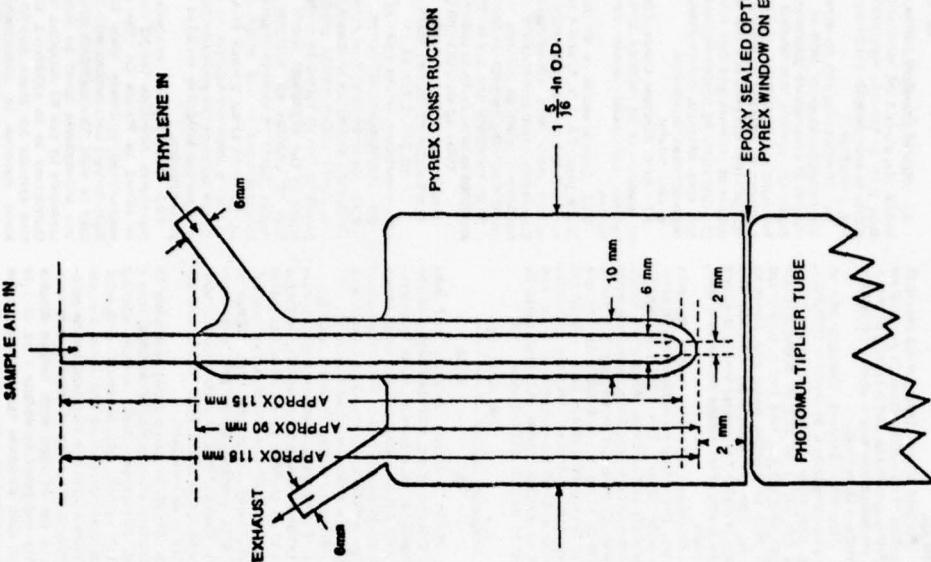


Figure D1. Detector cell.

[46 FR 22384, Nov. 25, 1981, as amended at 40 FR 7043, Feb. 16, 1978]

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### APPENDIX E—REFERENCE METHODS FOR DETERMINATION OF HYDROCARBONS CHARACTERISTIC FOR METHANE

#### 1. Principle and Applicability.

1.1 Measured volumes of air are delivered semicontinuously (4 to 12 times per hour) to a hydrogen flame ionization detector to measure its total hydrocarbon (THC) content. An aliquot of the same air sample is introduced into a stripper column which removes water, carbon dioxide, and hydrocarbons other than methane. Methane and carbon monoxide are passed quantitatively to a gas chromatographic column where they are separated. The methane is eluted first and is passed unchanged through a catalytic reduction tube into the flame ionization detector. The carbon monoxide is eluted into the catalytic reduction tube where it is reduced to methane before passing through the flame ionization detector. Between analyses the stripper column is backflushed to prepare it for subsequent analysis. Hydrocarbon concentrations corrected for methane are determined by subtracting the methane value from the total hydrocarbon value. Two modes of operation are possible: (1) A complete chromatographic analysis showing the continuous output from the detector for each sample injection; (2) The system is programmed to automatically switch to display a selected band width of the chromatogram. The peak height is then used as the measure of the concentration. The sample operation is referred to as the chromatographic or spectro mode and the latter as the barometric or "normal" mode depending on the mode of analyser.

1.2 The method is applicable to the semicontinuous measurement of hydrocarbons corrected for methane in ambient air. The carbon monoxide monitor, which is simultaneously obtained in this method, is not required in making measurements of hydrocarbons corrected for methane and will not be dealt with here.

#### 2. Range and Sensitivity.

2.1 Instruments are available with various range combinations. For atmospheric (0-40 p.p.m.) carbon (as  $\text{CH}_4$ ) and the methane range in 0-1.6 mg./m.<sup>3</sup> (0-10 p.p.m.). For special applications, lower ranges are available and in these applications the range for THC is 0-1.81 mg./m.<sup>3</sup> (0-8 p.p.m.) carbon (as  $\text{CH}_4$ ) and for methane the range is 0-1.81 mg./m.<sup>3</sup> (0-2 p.p.m.).

2.2 For the higher, atmospheric analysis ranges the sensitivity for THC is 0.065 mg./m.<sup>3</sup> (0.1 p.p.m.) carbon (as  $\text{CH}_4$ ) and for methane the sensitivity is 0.005 mg./m.<sup>3</sup> (0.005 p.p.m.). For the lower, special analysis ranges the sensitivity is 0.016 mg./m.<sup>3</sup> (0.025 p.p.m.) for each gas.

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#### 6. Interferences.

6.1 No interference in the methane measurement has been observed. The THC measurement typically includes all or a portion of what is generally classified as the air peak interferences. This effect is minimized by proper plumbing arrangements or is checked electronically.

6.2 Precision, Accuracy, and Stability.

6.3 Variations in ambient room temperature can cause changes in performance characteristics. This is due to shifts in oven temperature, flow rates, and pressure with ambient temperature change. The instrument should meet performance specifications with room temperature changes of  $\pm 3^\circ\text{C}$ . Baseline drift is automatically corrected in the barometric mode.

#### 5. APPARATUS.

5.1 Commercially Available THC,  $\text{CH}_4$ , and CO Analyzers. Instruments should be installed on location and decontaminated, preferably by the manufacturer, or his representative, to meet or exceed manufacturer's specifications and those described in this method.

5.2 Sample Introduction System. Pump, flow control valves, automatic switching valves, and downstair.

5.3 Filter (In-line). A binder-free, glassfiber filter with a porosity of 3 to 6 microns should be immediately downstream from the sample pump.

5.4 Stripper or Preconcentrator. Located outside of the oven at ambient temperature. The column should be replaced or replaced after the equivalent of 3 months of continuous operation.

5.5 Open. For containing the analytical column and catalytic converter. The oven should be capable of maintaining an elevated temperature constant within  $\pm 0.5^\circ\text{C}$ . The specific temperature varies with instrument manufacturer.

#### 6. Reagents.

6.1 Combustion Gas. Air containing less than 1.5 mg./m.<sup>3</sup> (2 p.p.m.) hydrocarbons as methane.

6.2 Fuel. Hydrogen or a mixture of hydrogen and inert gas containing less than 0.005 mg./m.<sup>3</sup> (0.1 p.p.m.) hydrocarbons as methane.

6.3 Carrier Gas. Helium, nitrogen, air, or hydrogen containing less than 0.005 mg./m.<sup>3</sup> (0.1 p.p.m.) hydrocarbons as methane.

#### 7. Procedure

7.1 Calibrate the instrument as described in 8.1. Introduce a sample into the system under the same conditions of pressure and flow rates as are used in calibration. (The pump is bypassed only when pressurized cylinder gases are used.) Figure E1 shows a typical flow diagram; for specific operating instructions refer to manufacturer's manual.

#### 8. Calibration.

8.1 Calibration Curve. Determine the linearity of the system for THC and methane in the barometric mode by introducing zero methane and adding the recorder setting controls to indicate a recorder reading of zero. Introduce the span gas and adjust the span recorder to indicate the proper value on the span recorder scale. Check zero and span until recorder scales no longer need adjustment. Introduce intermediate calibration gases and produce intermediate calibration curves and plot the values obtained. If a smooth curve is not obtained, calibration gases may need replacement.

#### 9. Determination.

9.1 Determine concentrations of total hydrocarbons (as  $\text{CH}_4$ ) and  $\text{CH}_4$  directly from the calibration curves. No calculations are necessary.

9.2 Determine concentration of hydrocarbons corrected for methane by subtracting the methane concentration from the total hydrocarbon concentration. The calibration curves. No calculations are necessary.

9.3 Conversion between p.p.m. and mg./ml. values for total hydrocarbons (as  $\text{CH}_4$ ) methane and hydrocarbons corrected for methane are made as follows:

$$\text{p.p.m. carbon (as } \text{CH}_4\text{)} = \frac{\text{mg. carbon (as }}{\text{CH}_4\text{)}}{(\text{m}^3/\text{m}^3) \times 1.03}$$

#### 10. Ratiographs.

10.1 "Attrib-Parameter" Air Quality Analyzer. ISA Proceedings AID/CHAMPID Symposium, Houston, Texas, April 19-21, 1971.

10.2 Chromatograph for Automatic Chromatographic Method for Methane, Nitrogen, Air, or Oxygen. Vilalobos, R., and Chapman, R. L., "A Gas Chromatograph for Automatic

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**App. E**

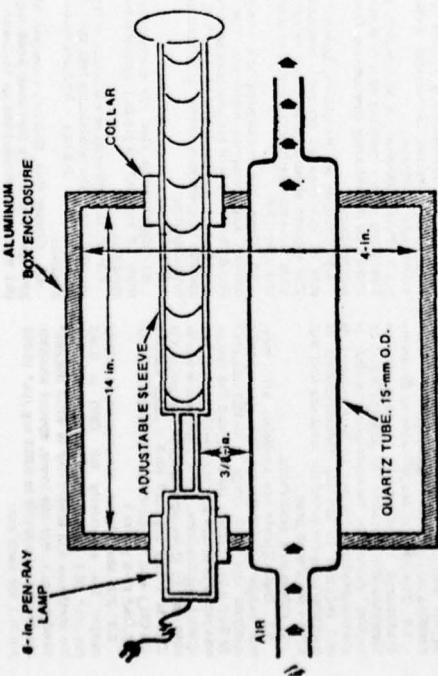


Figure D2. Ozone source.

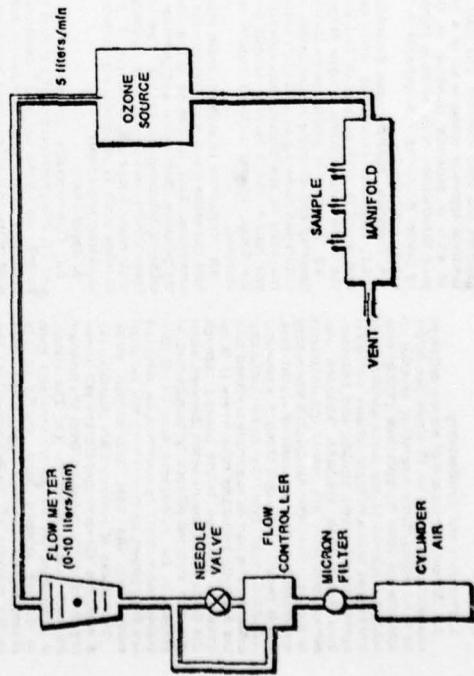


Figure D3. Ozone calibration air supply, source, and manifold system.

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**App. E**

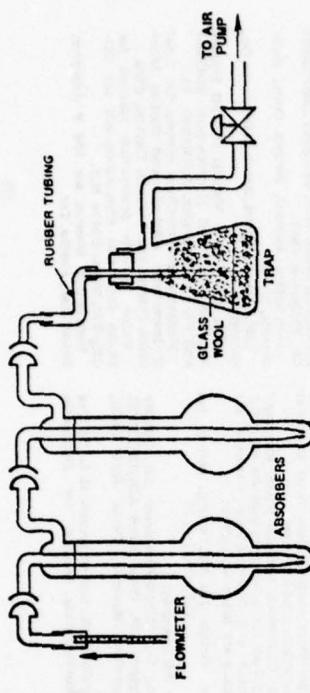


Figure D4. KI sampling train.

**A. Suggested Performance Specifications for Atmospheric Analyzers for Hydrocarbons Correctors for Methane:**

Range (minimum) ----- 0.5 mg./m.<sup>3</sup> (0-6 P.P.M.) THG  
0-3 mg./m.<sup>3</sup> (0-6 P.P.M.) CH<sub>4</sub>  
0-10 mg./m.<sup>3</sup> full scale.

Output (minimum) ----- 0.1 p.p.m. THC.  
0.1 p.p.m. CH<sub>4</sub>.

Minimum detectable sensitivity, zero drift (maximum) --- 1 percent/24 hours.

Span drift (maximum) --- 1 percent/24 hours.

Precision (minimum) --- ±0.5 percent.

Operational period (minimum) 3 days.

Operating temperature range (minimum) 5-40° C.

Operating humidity range (minimum) 10-100 percent.

Linearity (maximum) --- 1 percent of full scale.

**B. Suggested Definitions of Performance Specifications:**

Range—The minimum and maximum measurement limits.

Output—Electrical signal which is proportional to the measurement; intended for connection to readout or data processing devices. Usually expressed as millivolts or millamps full scale at a given impedance.

Pull Scale—The maximum measuring limit for a given range.

Minimum Detectable Sensitivity—The smallest amount of input concentration that can be detected as the concentration approaches zero.

Accuracy—The degree of agreement between a measured value and the true value; usually expressed as  $\pm$  percent of full scale.

Lag Time—The time interval from a step change in input concentration at the instrument inlet to the first corresponding change in the instrument output.

Time to 90 Percent Response—The time interval from a step change in the input concentration at the instrument inlet to a reading of 90 percent of the ultimate recorded concentration.

Rate Time (90 percent)—The interval between initial response time and time to 90 percent response after a step decrease in the input concentration.

Zero Drift—The change in instrument output over a stated time period, usually 24 hours, of undisturbed continuous operation, when the input concentration is zero; usually expressed as percent of full scale.

Span Drift—The change in instrument output over a stated time period, usually 24 hours, of undisturbed continuous operation, when the input concentration is a stated upscale value; usually expressed as percent of full scale.

Precision—The degree of agreement between repeated measurements of the same concentration. It is expressed as the average deviation of the single results from the mean.

Operational Period—The period of time over which the instrument can be expected to operate unattended within specifications.

Noise—Spontaneous deviations from a mean output not caused by input concentration changes.

Interference—An undesired positive or negative output caused by a substance other than the one being measured.

Interference Equivalence—The portion of indicated input concentration due to the presence of an interferent.

Operating Temperature Range—The range of ambient temperatures over which the instrument will meet all performance specifications.

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**Operating Humidity Range**—The range of ambient relative humidity over which the instrument will meet all performance specifications.

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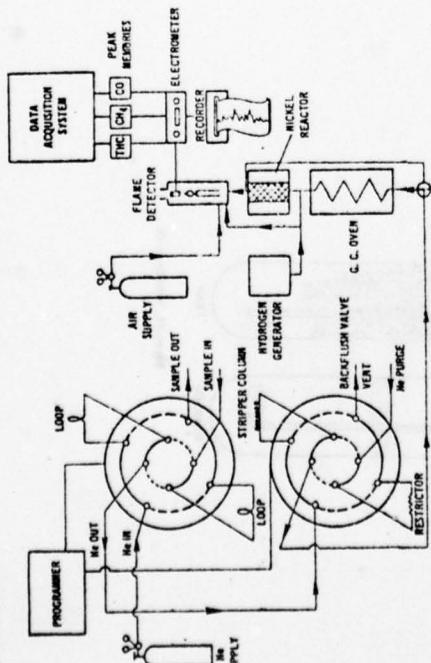


Figure E1. Typical flow diagram.

**APPENDIX F—REFERENCE METHODS FOR THE DETERMINATION OF NITROGEN DIAMINE IN AIR (24-HOUR SAMPLING METROPO)**

1. Principle and Applicability.

1.1 Nitrogen dioxide is collected by bubbling air through a sodium hydroxide solution to form a stable solution of sodium nitrite. The nitrite ion produced during sampling is determined colorimetrically by reacting the exposed absorbing reagent with phosphoric acid, sulfanilamide, and N-naphthylbenzidine dihydrochloride.

1.2 The method is applicable to collection of 24-hour samples in the field and subsequent analysis in the laboratory.

#### 2. Range and Sensitivity.

2.1 The range of the analysis is 0.04 to 1.6  $\mu\text{g}/\text{m}^3$  with 50 ml. absorbing reagent and a sampling rate of 200  $\text{ml}/\text{min}$ . For 24 hours, the range of the method is 20-740  $\mu\text{g}/\text{m}^3$  (0.01-0.4  $\mu\text{g}/\text{m}^3$ ) nitrogen dioxide.

2.2 A concentration of 0.04  $\mu\text{g}/\text{m}^3$  will produce an absorbance of 0.02 using 1-cm. cells.

#### 3. Interferences.

3.1 The interference of sulfur dioxide is eliminated by converting it to sulfuric acid with hydrogen peroxide before analysis.

3.2 Precision, Accuracy, and Stability.

3.3 The relative standard deviations are

1.6 percent and 21.5 percent at nitrogen dioxide concentrations of 160  $\mu\text{g}/\text{m}^3$  (0.072

μmolar) and 200  $\mu\text{g}/\text{m}^3$  (0.108  $\mu\text{molar}$ ), respectively, based on an automated analysis of samples collected from a standard test atmosphere.

3.4 When the analysis is performed manually, no accuracy data are available.

3.5 Samples are stable for at least 6 weeks.

#### 4. APPARATUS.

5.1 Sampler. See Figure P1.

5.1.1 Absorber. Polypropylene tubes 164 × 30 mm., equipped with polypropylene two-port closures. Rubber stoppers cause high and varying blank values and should not be used. A gas dispersion tube with a fritted end of porosity B (70-100  $\mu\text{m}$ , maximum pore diameter) is used.

5.1.2 Measuring Device. Carefully clean the frit with dichloroacetic-concentrated sulfuric acid cleaning solution and rinse well with distilled water. Insert through one side of a two-hole rubber stopper and install in a test tube containing sufficient distilled water to cover the fritted portion. Attach a vacuum source to the other hole of the rubber stopper and measure the vacuum required to draw the first perceptible stream of air bubbles through the frit. AppI7

the following equation:

$$Q = \frac{1.600}{A} \times 100$$

Q = Amount of  $\text{NaNO}_2$ , g.  
A = Assay, percent.

#### 5.2 Sampling.

5.2.1 Calibration of Flowmeter. Using a stopwatch and a stopwatch, determine the rates of air flow (ml./min.) through the flowmeter at several ball positions. Plot ball positions versus flow rates.

#### 5.2.2 Calibration of Hypodermic Needle.

Connect the calibrated flowmeter, the needle, and the source of vacuum in such a way that the direction of airflow through the needle is the same as in the sampling train. Read the position of the ball and determine flow rate in ml./min. from the calibration chart prepared in 5.1.1. Reject all needles not having flow rates of 100 to 210 ml./min. before sampling.

#### 5.2.3 Calibration Curve. Dilute 5.0 ml. of 1,000 $\mu\text{g}/\text{m}^3$ $\text{NO}_2$ /ml. solution to 200 ml. with absorbing reagent. This solution is the same as in the sampling train. Read the position of the ball and determine flow rate in ml./min. from the calibration chart prepared in 5.1.1. Reject all needles not having flow rates of 100 to 210 ml./min. before sampling.

#### 5.2.4 Sampling.

5.2.5 Absorbing Reagent. Dissolve 4.0 g. sodium hydroxide in distilled water and dilute to 1,000 ml.

#### 5.2.6 Analysts.

5.2.7 Sulfanilamide. Dissolve 20 g. sulfanilamide in 700 ml. distilled water. Add with mixing 50 ml. concentrated phosphoric acid (85 percent) and dilute to 1,000 ml. This solution is stable for a month if refrigerated.

5.2.8 NEDA Solution. Dissolve 0.5 g. N-naphthylethylenediamine dihydrochloride in 500 ml. of distilled water. This solution is stable for a month if refrigerated and protected from light.

5.2.9 Hydrogen Peroxide. Dilute 0.2 ml. 30 percent hydrogen peroxide to 250 ml. with distilled water. This solution may be used for a month if protected from light.

5.2.10 Standard Nitrite Solution. Dissolve sufficient dedicated sodium nitrite ( $\text{NaNO}_2$ ) assay of 97 percent or greater) and dilute with distilled water to 1,000 ml. so that a solution containing 1,000  $\mu\text{g}/\text{m}^3$   $\text{NO}_2$  is obtained. The amount of  $\text{NaNO}_2$  to use is calculated as follows:

$$Q = \frac{V}{A} \times 100$$

Q = Amount of  $\text{NaNO}_2$ , g.

A = Assay, percent.

1.600 = Gravimetric factor in converting  $\text{NO}_2$  to  $\text{NO}_2^-$ .

\*Available from Bel-Art Products, Pequannock, N.J.

\*\*Available from Fisher Scientific Co., Inc., Springfield, Mass.

†Available from Fisher Scientific Co., Inc., Springfield, Mass.

‡Available from Fisher Scientific Co., Inc., Springfield, Mass.

§Available from Fisher Scientific Co., Inc., Springfield, Mass.

||Available from Fisher Scientific Co., Inc., Springfield, Mass.

¶Available from Fisher Scientific Co., Inc., Springfield, Mass.

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$F_s$  = Measured flow rate after sampling.  
ml./min.

T = Time of sampling, min.

$10^{-4}$  = Conversion of ml. to m.<sup>3</sup>

b.2 Calculate the concentration of nitrogen dioxide as  $\mu\text{g. } \text{NO}_2/\text{m.}^3$ .

$$\mu\text{g. } \text{NO}_2/\text{m.}^3 = \frac{(\mu\text{g. } \text{NO}_2/\text{ml.}) \times 143}{V \times 0.35}$$

b.3 = Volume of absorbing reagent used in sampling, ml.

V = Volume of air sampled, m.<sup>3</sup>

$E$  = Efficiency.

0.35 = Efficiency.  
0.2 If desired, concentration of nitrogen dioxide may be calculated as  $\mu\text{g. } \text{NO}_2/\text{m.}^3$ .

p.p.m. = ( $\mu\text{g. } \text{NO}_2/\text{m.}^3$ )  $\times 6.23 \times 10^{-4}$ .

10. References.

- (1) Jacobs, M. B., and Hochbeiser, S., "Continuous Sampling and Ultramicrodetermination of Nitrogen Dioxide in Air," *Anal. Chem.*, 30, 623 (1958).
- (2) Purdie, L. J., Dudley, J. E., Clemens, J. B., and Thompson, R. J., "Studies in Air Sampling for Nitrogen Dioxide." I. A reinvestigation of the 'Jacobs-Hochbeiser Reagent.' In Preparation.

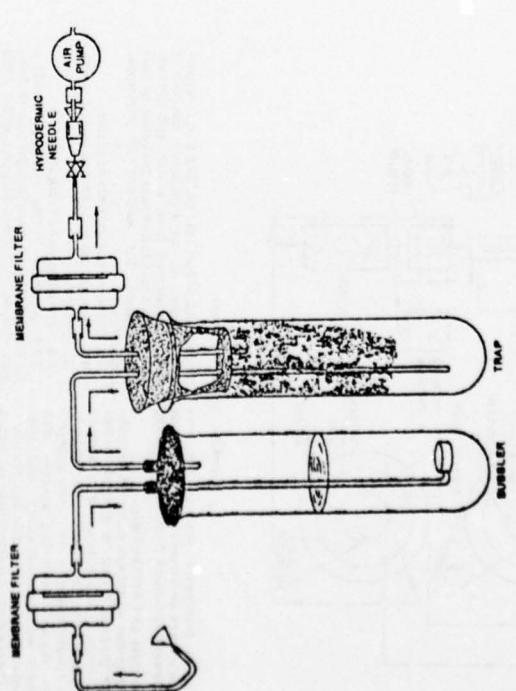


Figure F1. Sampling train.

II a

**APPENDIX II**

**AMBIENT AIR MONITORING REFERENCE  
AND EQUIVALENT METHODS  
(40 CFR 53)**

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### § 53.2 Title 40—Protection of Environment

Sec. 53.1 Applications for reference or equivalent method determinations.

53.3 Processing of applications.

53.5 Right to witness conduct of tests.

53.6 Testing of aerosols at the initiative of the Administrator.

53.7 Designation of reference and equivalent methods.

53.9 Conditions of designation.

53.10 Appeal from rejection of application.

53.11 Cancellation of reference or equivalent method designation.

53.12 Request for hearing on cancellation.

53.13 Hearings.

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53.15 Trade secrets and confidential or privileged information.

53.16 Submission of reference methods.

Subpart B—Procedures for Testing Performance Characteristics of Automated Methods

53.20 General provisions.

53.21 Test conditions.

53.22 Generation of test atmospheres.

53.23 Test procedures.

APPENDIX A—OPTIONAL FORMS FOR REPORTING TEST RESULTS

Subpart C—Procedures for Determining a Consistent Relationship Between Candidate Methods and Reference Methods

53.30 General provisions.

53.31 Test conditions.

53.32 Test procedures.

APPENDIX A—OPTIONAL FORM FOR REPORTING TEST RESULTS

AUTHORITY: Section 301(a) of the Clean Air Act (42 U.S.C. section 13878(a)), as amended by sec. 15(c)(2) of Public Law 91-504, 84 Stat. 1713.

SOURCE: 40 FR 7049, Feb. 16, 1975, unless otherwise noted.

#### Subpart A—General Provisions

##### § 53.1 Definitions.

(a) Terms used but not defined in this part shall have the meaning given them by the Act.

(b) "Act" means the Clean Air Act (42 U.S.C. 1857-1857f), as amended.

(c) "Agency" means the Environmental Protection Agency.

(d) "Administrator" means the Administrator of the Environmental Protection Agency or his authorized representative.

(e) "Reference method" means a method of sampling and analyzing the ambient air for an air pollutant that is specified as a reference method in an appendix to Part 50 of this chapter, or a method that has been designated as a

reference method in accordance with this part; it does not include a method for which a reference method designation has been cancelled in accordance with § 53.11 or § 53.16.

(f) "Equivalent method" means a method of sampling and analyzing the ambient air for an air pollutant that has been designated as an equivalent method in accordance with this part; it does not include a method for which an equivalent method designation has been cancelled in accordance with § 53.11 or § 53.16.

(g) "Candidate method" means a method of sampling and analyzing the ambient air for an air pollutant for which an application for a reference method determination or an equivalent method determination is submitted in accordance with § 53.4, or a method tested at the initiative of the Administrator in accordance with § 53.7.

(h) "Manual method" means a method for measuring concentrations of an ambient air pollutant in which sample collection, analysis, or measurement, or some combination thereof, is performed manually.

(i) "Automated method" or "analyzer" means a method for measuring concentrations of an ambient air pollutant in which sample collection, analysis, or measurement, or some combination thereof, is performed automatically.

(j) "Test analyzer" means an analyzer subjected to testing as a candidate method in accordance with Subpart B of this part, Subpart C of this part, or both, which sample collection, analysis, and measurement are performed automatically.

(k) "Applicant" means a person who submits an application for a reference or equivalent method determination under § 53.4, or a person who assumes the rights and obligations of an applicant under § 53.7.

(l) "Ultimate purchaser" means the first person who purchases a reference method or an equivalent method for purposes other than resale.

140 FR 7049, Feb. 16, 1975, as amended at 41 FR 11255, Mar. 17, 1976.]

§ 53.2 General requirements for a reference method determination.

(a) *Manual methods.* Except as provided in § 53.16, manual methods will not be considered for reference method determinations under this part.

Note: As defined in § 53.1(e), "reference method" includes a manual method specified in an appendix to Part 50 of this chapter. Except as provided in § 53.16, the provisions

of this part are inapplicable to such a method.

(b) *Automated methods.* A candidate automated method must utilize the measurement principle and calibration procedures specified in the appropriate appendix to Part 50 of this chapter and meet the requirements specified in Subpart B of this part.

Note: Except as provided in § 53.16, an automated method will not be considered for a reference method determination if a manual reference method is specified in the appropriate appendix to Part 50 of this chapter.

[41 FR 1255, Mar. 17, 1976]

§ 53.3 General requirements for an equivalent method determination.

(a) *Manual methods.* Candidate manual methods must satisfy the requirements specified in Subpart C of this part.

(b) *Automated methods.* Candidate automated methods must satisfy the requirements specified in Subparts B and C of this part.

§ 53.4 Applications for reference or equivalent method determinations.

(a) Applications for reference or equivalent method determinations shall be submitted in triplicate to:

Director, Quality Assurance & Environmental Monitoring Laboratory, Department 2, United States Environmental Protection Agency, National Environmental Research Center, Research Triangle Park, North Carolina 27711.

(b) Each application shall be signed by an authorized representative of the applicant, shall be marked in accordance with § 53.15 (if applicable), and shall contain the following:

(1) A clear identification of the candidate method which will distinguish it from all other methods and by which it may be referred to unambiguously.

(2) A detailed description of the candidate method including but not limited to the following: The measurement principle, manufacturer, name, model number, and other forms of identification; a listing of the significant components; schematic diagrams; and a detailed description of the apparatus and measurement procedures.

(3) A copy of a comprehensive opera-

tional or instruction manual providing a complete and detailed description of the operational and calibration procedures prescribed for field use of the candidate method and all instruments utilized as

## PART 53—AMBIENT AIR MONITORING REFERENCE AND EQUIVALENT METHODS

### Subpart A—General Provisions

#### Sec. 53.1 Definitions.

53.1 General requirements for a reference method determination.

53.2 General requirements for an equivalent method determination.

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### § 53.7

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part of that method. The manual shall include a clear description of installation and operation procedures and of necessary periodic maintenance, as well as comprehensive trouble-shooting and corrective maintenance procedures and safety precautions (see § 53.9(b)). For automated methods, the manual shall include a detailed description of potential safety-hazards that may result from normal use, or (if the method is automated) from normal use or malfunction, of the method and a description of the requirements (see § 53.9(b)).

After receiving an application for a reference or equivalent method determination, the Administrator will publish notice of the application in the Federal Register and, within 75 calendar days after receipt of the application, take one or more of the following actions:

(a) Send notice to the applicant in accordance with § 53.8, that the candidate method has been determined to be a reference or equivalent method;

(b) Send notice to the applicant that his application has been rejected, including a statement of reasons for rejection;

(c) Send notice to the applicant that additional information must be submitted before a determination can be made and specify the additional information that is needed (in such cases, the 75-day period shall commence upon receipt of the additional information);

(d) Send notice to the applicant that additional tests are necessary and specify what tests are necessary and how they shall be interpreted (in such cases, the 75-day period shall commence upon receipt of the additional test data); or

(e) Send notice to the applicant that additional tests will be conducted by the Administrator, specifying the nature of and reasons for the additional tests and the estimated time required (in such cases, the 75-day period shall commence 1 calendar day after the additional tests have been completed).

(4) A statement that the candidate method has been tested in accordance with the procedures described in Subpart B of this part, Subpart C of this part, or both, as applicable.

(5) Test data, records, calculations, and test results as specified in Subpart B of this part, Subpart C of this part, or both, as applicable.

(6) A statement that the method or analyzer tested in accordance with this part is representative of the candidate method described in the application.

(7) For candidate automated methods, the application shall also contain the following:

(1) A detailed description of the quality control program that will be utilized, if the candidate method is designated as a reference or equivalent method, to ensure that all analyzers offered for sale under that designation will have essentially the same performance characteristics as the analyzer tested in accordance with this part.

§ 53.6 Right to witness conduct of tests.

(a) Submission of an application for a reference or equivalent method determination shall constitute consent for the Administrator or his authorized representative, upon presentation of appropriate credentials, to witness or observe any tests required by this part in connection with the application or in connection with any modification or intended modification of the method by the applicant.

<sup>1</sup> Guidance for the development of such a manual may be found in the EPA report, "Guideline Specifications for the Development of Instruction Manuals for Automatic Air Monitoring Instruments," available from: National Technical Information Service, U.S. Department of Commerce, 5285 Port Royal Road, Springfield, Virginia 22151. (702-321-8543). An example manual based on the above report and titled (EPA 450/3-74-03) "Fully Proceduralized Instruction Manual for the Gasco Monitor, Model 8002" is available from the same source.

(2) Any tests by either party that are to be witnessed or observed by the other party shall be conducted at a time and place mutually agreeable to both parties.

#### § 53.7 Testing of methods at the initiative of the Administrator.

(a) In the absence of an application for a reference or equivalent method determination, the Administrator may conduct the tests required by this part for such a determination, may compile such other information as may be necessary in his judgment to make such a determination, and (c) the basis of the tests and information may determine that a method satisfies applicable requirements of this part.

(b) In the absence of an application requesting the Administrator to consider revising an appendix to Part 50 of this chapter in accordance with § 53.16, the Administrator may conduct such tests and compile such information as may be necessary in his judgement to make a determination under § 53.16(d) and on the basis of the tests and information make such a determination.

(c) If a method tested in accordance with this section is designated as a reference or equivalent method in accordance with § 53.8 or is specified as a reference as a reference method in accordance with § 53.16, any person who offers the method for sale as a reference or equivalent method thereafter shall assume the rights and obligations of an applicant for purposes of this part with the exception of those pertaining to submission and processing of applications. [40 FR 7049, Feb. 18, 1975, as amended at 41 FR 11256, Mar. 17, 1976]

#### § 53.8 Designation of reference and equivalent methods.

(a) A candidate method determined by the Administrator to satisfy the applicable requirements of this part shall be designated as a reference method or equivalent method (as applicable), and a notice of the designation shall be submitted for publication in the Final Register not later than 15 days after the determination is made.

(b) A notice indicating that the method has been determined to be a reference method or an equivalent method but has one or more selectable ranges, the label or sticker required by paragraph (d) of this section shall be placed in close proximity to the range selector and shall indicate clearly which range or ranges have been designated as parts of the reference or equivalent method.

(f) An applicant who offers analyzers for sale as reference or equivalent methods shall maintain an accurate and current list of the names and mailing addresses of all ultimate purchasers of such analyzers. For a period of seven years after publication of the reference

(c) The Administrator will maintain a current list of methods designated as a reference or equivalent methods in accordance with this part and will send a copy of the list to any person or group upon request. A copy of the list will be available for inspection or copying at EPA Regional Offices.

#### § 53.9 Conditions of designation.

Designation of a candidate method as a reference method or equivalent method shall be conditioned on the applicant's compliance with the following requirements. Failure to comply with any of the requirements shall constitute a ground for cancellation of the designation in accordance with § 53.11.

(a) Any method offered for sale as a reference or equivalent method shall be accompanied by a copy of the manual referred to in § 53.4(b)(3) when delivered to any ultimate purchaser.

(b) Any method offered for sale as a reference or equivalent method shall generate no unreasonable hazard to operators or to the environment during normal use or (if the method is automated) during normal use or when, (c) Any analyzer offered for sale as a reference or equivalent method shall function within the limits of the performance specifications referred to in § 53.20(a) for at least 1 year after delivery and acceptance when maintained and operated in accordance with the manual referred to in § 53.4(b)(3).

(d) Any analyzer offered for sale as a reference or equivalent method shall bear a prominent, permanently affixed label or sticker indicating that the analyzer has been designated by EPA as a reference method or as an equivalent method (as applicable) in accordance with this part.

(e) If an analyzer is offered for sale as a reference or equivalent method but has one or more selectable ranges, the label or sticker required by paragraph (d) of this section shall be placed in close proximity to the range selector and shall indicate clearly which range or ranges have been designated as parts of the reference or equivalent method.

(f) An applicant who offers analyzers for sale as reference or equivalent methods shall maintain an accurate and current list of the names and mailing addresses of all ultimate purchasers of such analyzers. For a period of seven years after publication of the reference

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or equivalent method designation applicable to such an analyzer, the applicant shall notify all ultimate purchasers of the analyzer within 30 days if the designation has been cancelled in accordance with § 53.11 or § 53.16 or if adjustment of the analyzer is necessary under § 53.11(b).

(g) If an applicant modifies an analyzer that has been designated as a reference or equivalent method, the applicant shall not sell the analyzer as modified as a reference or equivalent method nor attach a label or sticker to the analyzer as modified under paragraph (d) or (e) of this section until he has received notice under § 53.14(c) that the existing designation or a new designation will apply to the analyzer as modified or has applied for and received notice under § 53.8(b) of a new reference or equivalent method determination for the analyzer as modified.

[40 FR 7049, Feb. 18, 1975, as amended at 41 FR 11350, Mar. 17, 1976]

#### § 53.10 Appeal from rejection of application.

Any applicant whose application for a reference or equivalent method determination has been rejected may appeal the Administrator's decision by taking one or more of the following actions:

(a) The applicant may submit new or additional information in support of the application.

(b) The applicant may request that the Administrator reconsider the data and information already submitted.

(c) The applicant may request that any test conducted by the Administrator that was a material factor in his decision to reject the application be repeated.

§ 53.11 Cancellation of reference or equivalent method designation.

(a) **Preliminary finding.** If the Administrator makes a preliminary finding on the basis of any information available to him that a representative sample of a method designated as a reference or equivalent method and offered for sale as such does not fully satisfy the requirements of this part or that there is any violation of the requirements set forth in § 53.9, he may initiate proceedings to cancel the designation in accordance with the following procedures.

(b) **Notification and opportunity to demonstrate or achieve compliance.** (1)

After making a preliminary finding in accordance with paragraph (a) of this

section, the Administrator will send notice of the preliminary finding to the applicant, together with a statement of the facts and reasons on which the preliminary finding is based, and will publish notice of the preliminary finding in the Federal Register.

(2) The applicant will be afforded an opportunity to demonstrate or to achieve compliance with the requirements of notice in accordance with paragraph (b) of this section or within such further period as the Administrator may allow, by demonstrating to the satisfaction of the Administrator that the method in question satisfies the requirements of this part, by commencing a program to make any adjustments that are necessary to bring the method into compliance, or by taking such action as may be necessary to cure any violation of the requirements of § 53.9. If adjustments are necessary to bring the method into compliance, all such adjustments shall be made within a reasonable time as determined by the Administrator. If the applicant demonstrates or achieves compliance in accordance with this paragraph (b)(2), the Administrator will publish notice of such demonstration or achievement in the *Federal Register*.

(c) **Request for hearing.** Within 60 days after publication of notice in accordance with paragraph (b)(1) of this section, the applicant or any interested person may request a hearing as provided in § 53.12.

(d) **Notice of cancellation.** If, at the end of the period referred to in paragraph (b)(2) of this section, the Administrator determines that the reference or equivalent method designation should be cancelled, he will publish a notice of cancellation in the *Federal Register* and delete the designation from the list maintained under § 53.8(c). If a hearing has been requested and granted in accordance with § 53.12, action under this paragraph (d) will be taken only after completion of proceedings (including any administrative review) conducted in accordance with § 53.13 and only if the decision of the Administrator reached in such proceedings is that the designation in question should be cancelled.

§ 53.12 Request for hearing on cancellation.

(a) **Notification and opportunity to demonstrate or achieve compliance.** (1)

Within 60 days after publication of notice in accordance with § 53.11(b)(1),

the applicant or any interested person may request a hearing on the Administrator's action. The request shall be in writing, signed by an authorized representative of the applicant or interested person, and shall include a statement specifying (a) any objections to the Administrator's action and (b) data or other information in support of such objections. If, after reviewing the request and supporting data, the Administrator finds that the request raises a substantial issue of fact, he will grant a hearing in accordance with § 53.13 with respect to such issue.

#### § 53.13 Hearings.

(a) (1) After granting a request for a hearing under § 53.12, the Administrator will designate a presiding officer for the hearing.

(2) If a time and place for the hearing have not been fixed by the Administrator, the hearing will be held as soon as practicable at a time and place fixed by the presiding officer, except that the hearing shall, in no case, be held sooner than 30 days after publication of a notice of hearing in the *Federal Register*.

(3) For purposes of the hearing, the parties shall include the Environmental Protection Agency, the applicant or interested person(s) who requested the hearing, and any person permitted to intervene in accordance with paragraph (c) of this section.

(4) The Deputy General Counsel or his representative will represent the Environmental Protection Agency in any hearing before the presiding officer.

(5) Each party other than the Environmental Protection Agency may be represented by counsel or by any other duly authorized representative.

(b) (1) Upon his appointment, the presiding officer will establish a hearing file. The file shall contain copies of the notices issued by the Administrator pursuant to § 53.11(b)(1), together with any accompanying material, the request for a hearing and supporting data submitted therewith, the notice of hearing published in accordance with paragraph (a)(2) of this section, and correspondence and other material data relevant to the hearing.

(2) The hearing file shall be available for inspection by the parties or their representatives at the office of the presiding officer, except to the extent that it contains information identified in accordance with § 53.15.

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(c) At his discretion, the presiding officer may permit any interested person to intervene in the hearing upon such showing of interest as the presiding officer may require; provided that leave to intervene may be denied in the interest of expediting the hearing where it appears that the interests of the person seeking to intervene will be adequately represented by another party (or by other parties), including the Environmental Protection Agency.

(d) (1) The presiding officer, upon the request of any party or at his discretion, may arrange for a prehearing conference at a time and place specified by him to consider the following:

(i) Simplification of the issues.

(ii) Stipulations, admissions of fact,

and the introduction of the number of expert witnesses.

(iv) Possibility of agreement disposing of all or any of the issues in dispute.

(v) Such other matters as may aid in the disposition of the hearing, including such additional tests as may be agreed upon by the parties.

(2) The results of the conference shall be reduced to writing by the presiding officer and made part of the record.

(2) Witnesses shall be placed under oath.

(3) Any witness may be examined or cross-examined by the presiding officer, or their representatives. The presiding officer may, at his discretion, limit cross-examination to relevant and material issues.

(4) Hearings shall be reported verbatim. Copies of transcripts of proceedings may be purchased from the reporter.

(5) All written statements, charts, tabulations, and data offered in evidence at the hearing shall, upon a showing satisfactory to the presiding officer of their authenticity, relevance, and materiality, be received in evidence and shall constitute part of the record.

(6) Oral argument shall be permitted. The presiding officer may limit oral presentations to relevant and material issues and designate the amount of time allowed for oral argument.

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(D) (1) The presiding officer shall make an initial decision which shall include written findings and conclusions and the reasons therefor on all the material issues of fact, law, or discretion presented on the record.

(2) Within 30-calendar days after receiving a report under paragraph (a) of this section, the Administrator will take one or more of the following actions:

(1) Notify the applicant that the designation will continue to apply to the method if the modification is implemented.

(2) Send notice to the applicant that a new designation will apply to the method (as modified) if the modification is implemented, submit notice of the determination for publication in the FEDERAL REGISTER, and revise or supplement the list referred to in § 53.8(c) to reflect the determination.

(3) Send notice to the applicant that the designation will not apply to the method (as modified). If the modification is implemented and submit notice of the determination for publication in the FEDERAL REGISTER;

(4) Send notice to the applicant that additional information must be submitted before a determination can be made and specify the additional information that is needed (in such cases, the 30-day period shall commence upon receipt of the additional information);

(5) Send notice to the applicant that additional tests are necessary and specify what tests are necessary and how they shall be interpreted (in such cases, the 30-day period shall commence upon receipt of the additional test data); or

(6) Send notice to the applicant that additional tests will be conducted by the Administrator and specify the reasons for and the nature of the additional tests to be conducted (in such cases, the 30-day period shall commence one calendar day after the additional tests are completed).

(d) An applicant who has received a notice under paragraph (c)(3) of this section may appeal the Administrator's action as follows:

(1) The applicant may submit new or additional information pertinent to the intended modification.

(2) The applicant may request the Administrator to reconsider data and information already submitted.

(3) The applicant may request that the Administrator repeat any test he conducted that was a material factor in his determination. A representative of

the applicant may be present during the performance of any such test.

160 FR 7049, Feb. 18, 1975, as amended at 40 FR 18168, Apr. 10, 1976; 41 FR 11246, Mar. 17, 1976.]

#### **§ 53.15 Trade secrets and confidential or privileged information.**

Any information submitted under this part that is claimed to be a trade secret or confidential or privileged information shall be marked or otherwise clearly identified as such in the submittal. Information so identified will be treated in accordance with Part 2 of this chapter (concerning public information).

#### **§ 53.16 Suppression of reference methods.**

(a) This section prescribes procedures and criteria applicable to requests that the Administrator specify a new reference method, or a new measurement principle and calibration procedure on which reference methods shall be based, by notice of the appropriate appendix to Part 50 of this chapter. Such action will ordinarily be taken only if the Administrator determines that a candidate method or a variation thereof is substantially superior to the existing reference methods.

(b) In exercising his discretion under this section, the Administrator will consider: (1) The benefits, in terms of the requirements and purposes of the Act, that would result from specifying a new reference method or a new measurement principle and calibration procedure; (2) the potential economic consequences of such action for State and local control agencies; and (3) any disruption of State and local air quality monitoring programs that might result from such action.

(c) An applicant who wishes the Administrator to consider revising an appendix to Part 50 of this chapter on the ground that the applicant's candidate method is substantially superior to the existing reference method(s) shall submit an application for a reference or equivalent method determination in accordance with § 53.4, and shall indicate therein that he desires such consideration. The application shall include, in addition to the information required under § 53.4, data and any other information supporting the applicant's claim that the candidate method is substantially superior to the existing reference method(s).

(d) After receiving an application under paragraph (c) of this section, the Administrator will publish a notice of proposed rulemaking in the FEDERAL REGISTER. The notice will indicate that the Administrator proposes: (1) to revise the appendix in question; (2) where the appendix specifies a measurement principle and calibration procedure, to cancel reference method designations based on the appendix; and (3) to cancel equivalent method designations based on the existing reference method(s). The notice will include the terms or substance of the proposed revision, will indicate what periods of time the Administrator proposes to allow for replacement of existing methods under § 51.17(a)(4) of this chapter, and will solicit public comments on the proposal with particular reference to the considerations set forth in paragraphs (a) and (b) of this section.

(2) If, after consideration of comments received, the Administrator deter-

mines that it is appropriate to propose a revision of the appendix in question and send notice of the determination to the applicant;

(2) Determine that it is inappropriate to propose a revision of the appendix in question, determine whether the candidate method is a reference or equivalent method, and send notice of the determinations, including a statement of reasons for the determination, not to propose a revision to the applicant;

(3) Send notice to the applicant that additional information must be submitted before a determination can be made and specify the additional information that is needed (in such cases, the 75-day period shall commence upon receipt of the additional test data); or

(4) Send notice to the applicant that additional tests are necessary, specifying what tests are necessary and how they shall be interpreted (in such cases, the 75-day period shall commence upon receipt of the additional test data); or

(5) Send notice to the applicant that additional tests will be conducted by the Administrator, specifying the nature of and reasons for the additional tests and the estimated time required (in such cases, the 75-day period shall commence one calendar day after the additional tests have been completed).

(e) (1) After making a determination under paragraph (d) (1) of this section, the Administrator will publish a notice of proposed rulemaking in the FEDERAL REGISTER. The notice will indicate that the Administrator proposes: (1) to revise the appendix in question; (2) where the appendix specifies a measurement principle and calibration procedure, to cancel reference method designations based on the appendix; and (3) to cancel equivalent method designations based on the existing reference method(s). The notice will include the terms or substance of the proposed revision, will indicate what periods of time the Administrator proposes to allow for replacement of existing methods under § 51.17(a)(4) of this chapter, and will solicit public comments on the proposal with particular reference to the considerations set forth in paragraphs (a) and (b) of this section.

(2) If, after consideration of comments received, the Administrator deter-

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etermines that the appendix in question should be revised, he will by publication in the Federal Register: (i) promulgate the proposed revision, with such modifications as may be appropriate in view of comments received; (ii) where the appendices (prior to revision) specifies a measurement principle and calibration procedure, cancel reference method designations based on the appendix; (iii) cancel equivalent method designations based on the existing reference method(s); and (iv) specify the period(s) during which it will be allowed for replacement of existing methods under § 51.17(a)(4) of this chapter, with such modifications to the proposed period(s) as may be inappropriate in view of comments received. Cancelled designations will be deleted from the list, maintained under § 53.8(c). The requirements and procedures for cancellation set forth in § 53.11 shall be inapplicable to cancellation of reference or equivalent method designations under this section.

(3) If one specimen in question is representative of a new measurement principle and a sampling procedure on which the applicant's candidate method is based, the Administrator will take appropriate action under § 53.5 to determine whether the candidate method is a reference method.

(4) Upon taking action under paragraph (e)(1) of this section, the Administrator will send notice of the action to all applicants for whose methods reference and equivalent method clearance

lative or, values), all such determinations are cancelled by such action.

(f) An applicant who has received a notice of a determination under paragraph (d) (2) of this section may appeal the determination by taking one or more of the following actions:

(1) The applicant may submit new or additional information in support of the application.

(2) The applicant may request that the Administrator reconsider the data and information already submitted.

(3) The applicant may request that the test conducted by the Administrator

(c) For each performance specification (except Range), the test procedure shall be initially repeated seven (7) times to yield 7 test results. Each result shall be compared with the corresponding specification in Table B-1. A value higher than or outside that specified constitutes a failure. These 7 results for each parameter shall be interpreted as follows:

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(1) Zero (0) failures: candidate method passes the performance parameter.

(2) Three (3) or more failures: candidate method fails the performance parameter.

(3) One (1) or two (2) failures: Repeat the test procedures for the parameter eight (8) additional times yielding a total of fifteen (15) test results. The combined total of 15 test results shall then be interpreted as follows:

- (i) One (1) or two (2) failures: candidate method passes the performance parameter.
- (ii) Three (3) or more failures: candidate method fails the performance parameter.

TABLE B-1. PERFORMANCE SPECIFICATIONS FOR AUTOMATED METHODS

Performance Parameter	Units	Sulfur dioxide	Oxidants	Carbon monoxide	Definition and test procedures
1. Range.....	Parts per million.....	0-0.6	0-0.6	0-50	53.2(a)
2. None.....	do.....	0.05	0.05	0.50	53.2(b)
3. Lower detectable limit.....	do.....	0.01	0.01	1.0	53.2(c)
4. Interference Equivalent.....	do.....	do.....	do.....	do.....	53.2(d)
5. 24 hour integral mean.....	do.....	do.....	do.....	do.....	53.2(e)
6. 24 hr. mean draft, 12 and 24 hr.....	do.....	do.....	do.....	do.....	53.2(f)
7. 20 percent of upper range limit.....	Percent.....	±20.0	±20.0	±10.0	53.2(g)
8. 20 percent of upper range limit.....	Miligrams.....	20	20	10	53.2(h)
9. 24 hr. mean draft, 12 and 24 hr.....	do.....	do.....	do.....	do.....	53.2(i)
10. Fall time.....	do.....	do.....	do.....	do.....	53.2(j)
11. 20 percent of upper range limit.....	Parts per million.....	0.01	0.01	0.01	53.2(k)

<sup>1</sup> To convert from parts per million to micrograms per cubic meter at 25°C and 760 mm Hg, multiply by 0.0247.

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(d) The tests for zero drift, span drift, lag time, rise time, fall time, and precision shall be combined into single sequential procedure to be conducted at no more than one test point and ambient temperature.

in the manual referred to in § 53.4(b).  
(3) Allow adequate warm-up or stabil-  
ization time as indicated in the operat-  
ing instructions before beginning the  
tests. If the candidate method does not  
include an integral strip chart recorder,  
connect the output signal of the test  
analyzer to a suitable strip chart re-  
corder or the servo, null-balance type.  
This recorder shall have a chart width of  
at least 25 centimeters, chart speeds up

tration units according to the calibration curve constructed in accordance with § 53.21(b).  
(f) All recorder chart tracings, records, test data and other documentation obtained from or pertinent to these tests to 10 cm per hour, a response time of 1 second or less, a deadband of not more than 0.25 percent of full scale, and capability either of reading in measurements at least 5 percent below zero or of offsetting the zero by at least 5 percent.

**Note.**—Suggested formats for reporting the test results and calculations are provided in Part II.

**140 FR 7049, Feb. 18, 1975, as amended at**  
**Figures B-2, B-3, B-4, B-5, and B-6 in Appendix A. Symbols and abbreviations used in this support are listed in Table B-5, Appendix**  
**(b) Calibration of the West analyzer shall be as indicated in the manual referred to in § 53.4(b) (3) and as follows:**

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zero capability, adjust either the controls of the test analyzer or the chart recorder to obtain a  $\pm 5\%$  offset zero reading on the recorder chart to facilitate observing negative response or drift. If the candidate method is not capable of negative response, the test analyzer (not recorder) shall be operated with an offset zero.

Construct and submit a calibration curve showing a plot of recorder scale readings (ordinate) against pollutant concentrations (abscissa). A plot of output units (volts, millivolts, millamps, etc.) against pollutant concentrations shall also be shown for methods not including an integral chart recorder. All such plots shall consist of at least seven ( $>7$ ) approximately equally spaced, identifiable points, including 0 and  $90 \pm 5$  percent of full scale.

(c) Once the test analyzer has been set up and calibrated and the tests started, manual adjustment or normal periodic maintenance is permitted only every 3 days. Automatic adjustments which the test analyzer performs by itself are permitted at any time. The submitted records shall show clearly when any manual adjustment or periodic maintenance was made and describe the operations performed.

(d) If the test analyzer should malfunction during any of the performance tests, the tests for that parameter shall be repeated. A detailed explanation of the malfunction, remedial action taken, and whether recalibration was necessary (along with all pertinent maintenance charts) shall be submitted. If more than

one malfunction occurs, all performance test procedures for all parameters shall be repeated.

(e) Tests for all performance parameters shall be completed on the same test analyzer, except that use of multiple test analyzers to accelerate testing will be permitted when alternate ranges of a multi-range candidate method are being tested.

**§ 53.92 Generation of test atmospheres.** (a) Table B-2 specifies preferred methods for generating test atmospheres and suggested methods of verifying the concentrations. Only one means of establishing the concentration of a test atmosphere is normally required. If the method of generation can produce reproducible concentrations, verification is optional. If the method of generation is not reproducible, then establishment of the concentration by some verification method is required. However, when a method of generation other than that given in Table B-2 is used, the test concentration shall be verified.

(b) The test atmosphere delivery system shall be designed and constructed so as not to significantly alter the test atmospheric composition or concentration during the period of the test. The delivery system shall be fabricated from borosilicate glass or FEP Teflon.

(c) The output of the test atmosphere generation system shall be sufficiently stable to obtain stable response during the required tests. If a permeation device is used for generation of a test atmosphere, the device, as well as the air passing over it, shall be controlled to  $\pm 0.1^\circ\text{C}$ .

Table B-2. Test Atmospheres

Test gas	Generation	Verification
Ammonia.....	Permeation device. Simulate to system described in table B-3.	NBS-certified standards wherever possible. If NBS standards are not available, obtain 2 standards from independent sources which are within 2 percent of each other. Submit one standard to an independent laboratory for analysis which must agree with 2 percent of the supplier's nominal analysis.
Carbon dioxide.....	Cylinder of zero air or nitrogen containing CO <sub>2</sub> as required to obtain the concentration specified in table B-3.	Use NBS-certified standards wherever possible. If NBS standards are not available, obtain 2 standards from independent sources which are within 2 percent of each other. Submit one standard to an independent laboratory for analysis which must agree with 2 percent of the supplier's nominal analysis.
Carbon monoxide.....	Cylinder of zero air or nitrogen containing CO as required to obtain the concentration specified in table B-3.	Use NBS-certified standards wherever possible. If NBS standards are not available, obtain 2 standards from independent sources which are within 2 percent of each other. Submit one standard to an independent laboratory for analysis which must agree with 2 percent of the supplier's nominal analysis.
Ethane.....	Cylinder of prepurified nitrogen containing ethane as required to obtain the concentration specified in table B-3.	Use NBS-certified standards wherever possible. If NBS standards are not available, obtain 2 standards from independent sources which are within 2 percent of each other. Submit one standard to an independent laboratory for analysis which must agree with 2 percent of the supplier's nominal analysis.
Hydrogen chloride.....	Cylinder of prepurified nitrogen containing hydrogen chloride as required to obtain the concentration specified in table B-3.	Collect samples in bubbler containing distilled water acidulated by the mercurophenothiazine method. ASTM (D512), p. 23, reference 4.
Hydrogen sulfide.....	Permeation device system described in reference 1 and 2.	Tentative method of analysis for H <sub>2</sub> S content of the atmosphere, p. 40, reference 5.

Table B-2. Test Atmospheres—Continued

Test gas	Generation	Verification
Methane.....	Cylinder of zero air containing methane as required to obtain the concentration specified in table B-4.	Use NBS-certified standards wherever possible. If NBS standards are not available, obtain 2 standards from independent sources which are within 2 percent of each other. Submit one standard to an independent laboratory for analysis which must agree with 2 percent of the supplier's nominal analysis.
Nitric oxide.....	Nitric oxide cylinder at approximately 100 ppm. Dilute with zero air to a suitable concentration as described in reference 6.	Use NBS-certified standards wherever possible. If NBS standards are not available, obtain 2 standards from independent sources which are within 2 percent of each other. Submit one standard to an independent laboratory for analysis which must agree with 2 percent of the supplier's nominal analysis.
Nitrogen dioxide.....	1. Gas phase dilution as described in reference 6. 2. Permeation device, similar to system described in reference 1 and 2.	Use NBS-certified standards wherever possible. If NBS standards are not available, obtain 2 standards from independent sources which are within 2 percent of each other. Submit one standard to an independent laboratory for analysis which must agree with 2 percent of the supplier's nominal analysis.
Ozone.....	Calibrated ozone generator as described in reference 6.	Use NBS-certified standards wherever possible. If NBS standards are not available, obtain 2 standards from independent sources which are within 2 percent of each other. Submit one standard to an independent laboratory for analysis which must agree with 2 percent of the supplier's nominal analysis.
Sulfur dioxide.....	Permeation device system described in reference 6.	Use NBS-certified standards wherever possible. If NBS standards are not available, obtain 2 standards from independent sources which are within 2 percent of each other. Submit one standard to an independent laboratory for analysis which must agree with 2 percent of the supplier's nominal analysis.
Water.....	Pas zero air through distilled water at a fixed known temperature between 20° and 30° C. such that the air stream becomes saturated. In table B-3, indicate zero air to concentration specified in table B-3.	Measure relative humidity by means of a dew-point indicator, calibrated electrolytic or piezoelectric hygrometer, or psychrometric thermometer.
Xylyne.....	Orifice of prepurified nitrogen containing 100 ppm xylene. Dilute with zero air to concentration specified in table B-3.	Use NBS-certified standards wherever possible. If NBS standards are not available, obtain 2 standards from independent sources which are within 2 percent of each other. Submit one standard to an independent laboratory for analysis which must agree with 2 percent of the supplier's nominal analysis.
Zero air.....	1. Ambient air purified by appropriate methods or other devices such that it is free of contaminants likely to cause a detectable response on the analyzer. 2. Cylinder of compressed zero air certified by the supplier or an independent laboratory to be free of contaminants likely to cause a detectable response on the analyzer.	1 Use stainless steel pressure regulator dedicated to the pollutant measured. Reference 1. O'Keefe, A. E., and Ortman, G. C. "Primary Standards for Trace Gas Analyses," <i>Anal. Chem.</i> , 28, 760 (1956). Reference 2. Pernicelli, F. P., A. E., Rosenberg, Z., and Bell, J. P., "Primary Standards for Trace Gas Analyses," <i>Anal. Chem.</i> , 30, 1033 (1958). Reference 3. "Tentative Method of Analysis for Ammonia in the Atmosphere (Indophenol Method)," <i>Health Lab. Service</i> , vol. 10, No. 2, 115-118, April 1973. Reference 4. 1973 Annual Book of ASTM Standards, American Society for Testing and Materials, 1916 Race St., Philadelphia, Pa. Reference 5. <i>Methods for Air Sampling and Analysis</i> , Interagency Committee, 1972, American Public Health Association, 1015, No. 110, Tentative Method for the Continuous Measurement of Nitrogen Dioxide (Chemoluminescence), addendum C, June 4, 1973. Reference 6. <i>Federal Register</i> , vol. 36, No. 225, National Primary and Secondary Ambient Air Quality Standards, Nov. 26, 1971.

- 1 Use stainless steel pressure regulator dedicated to the pollutant measured.  
Reference 1. O'Keefe, A. E., and Ortman, G. C. "Primary Standards for Trace Gas Analyses," *Anal. Chem.*, 28, 760 (1956).  
Reference 2. Pernicelli, F. P., A. E., Rosenberg, Z., and Bell, J. P., "Primary Standards for Trace Gas Analyses," *Anal. Chem.*, 30, 1033 (1958).  
Reference 3. "Tentative Method of Analysis for Ammonia in the Atmosphere (Indophenol Method)," *Health Lab. Service*, vol. 10, No. 2, 115-118, April 1973.  
Reference 4. 1973 Annual Book of ASTM Standards, American Society for Testing and Materials, 1916 Race St., Philadelphia, Pa.  
Reference 5. *Methods for Air Sampling and Analysis*, Interagency Committee, 1972, American Public Health Association, 1015, No. 110, Tentative Method for the Continuous Measurement of Nitrogen Dioxide (Chemoluminescence), addendum C, June 4, 1973.  
Reference 6. *Federal Register*, vol. 36, No. 225, National Primary and Secondary Ambient Air Quality Standards, Nov. 26, 1971.
- (a) Range—(1) Technical Definition. Nominal minimum and maximum con-



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(C) Test atmosphere 2: Zero air.

(iv) Adjust the individual flow rates and the pollutant or interference generators for the three test atmospheres as follows:

(A) The flow rates of test atmospheres 1 and 2 shall be identical.

(B) The concentration of pollutant in test atmosphere P shall be adjusted such that when P is mixed (diluted) with either test atmosphere 1 or 2, the resulting concentration of pollutant shall be equal to the value specified in Table B-3.

(C) The concentration of interference in test atmosphere I shall be adjusted such that when I is mixed (diluted) with test atmosphere P, the resulting concentration of interference shall be equal to the value specified in Table B-3.

(D) To minimize concentration errors due to flow rate difference between I and 2, it is recommended that, when possible, the flow rate of P from 10 to 20 times larger than the flow rates of I and 2.

(v) Mix test atmospheres P and Z by passing the total flow of both atmospheres through a mixing flask.

(vi) Sample and measure the mixture of test atmospheres P and Z with the test analyzer. Allow for a stable reading, record the reading, in concentration units, as R (see Figure B-3).

(vii) Mix test atmospheres P and I by passing the total flow of both atmospheres through a mixing flask.

(viii) Sample and measure this mixture. Record the stable reading, in concentration units, as  $R_i$ .

(ix) Calculate the interference equivalent ( $I/E$ ) as:

$$I/E = R_i - R$$

$I/E$  must be equal to or less than the specification given in Table B-1 for each interferent to pass the test.

(x) Follow steps (vii) through (ix). In turn, to determine the interference equivalent for each interferent.

(xi) For those interferents which cannot be mixed with the pollutant, as indicated by footnote (3) in Table B-3, adjust the concentration of test atmosphere I to the specified value without being mixed or diluted by the pollutant test atmosphere. Determine  $I/E$  as follows:

(A) Sample and measure test atmosphere Z (zero air). Allow for a stable reading and record the reading, in concentration units, as  $R_z$ .

(B) Sample and measure the interference test atmosphere I. If the test analysis

er is not capable of negative readings, adjust the analyzer (not the recorder) to give an offset zero. Record the stable reading in concentration units as  $R_i$ , extrapolating the calibration curve, if necessary, to represent negative readings.

(C) Calculate  $I/E = R_z - R_i$ .  $I/E$  must be equal to or less than the specification in Table B-1 to pass the test.

(xi) Sum the absolute value of all the individual interference equivalents. This sum must be equal to or less than the total interference specification given in Table B-1 to pass the test.

(e) Zero Drift, Span Drift, Lag Time, Rise Time, Full Time, and Precision—(1) Technical Definitions—(i) Zero Drift:

The change in response to zero pollutant concentration, over 12- and 24-hour periods of continuous unadjusted operation.

(ii) Span Drift: The percent change in response to an up-scale pollutant concentration over a 24-hour period of continuous unadjusted operation.

(iii) Lag Time: The time interval between a step change in input concentration and the first observable corresponding change in response.

(iv) Rise Time: The time interval between initial response and 95 percent final response after a step increase in input concentration.

(v) Full Time: The time interval between initial response and 95 percent of final response after a step decrease in input concentration.

(vi) Precision: Variation about the mean of repeated measurements of the same pollutant concentration, expressed as one standard deviation about the mean.

(2) Tests for these performance parameters shall be accomplished over a period of seven (7) or more days. During this time, the line voltage supplied to the test analyzer and the ambient temperature surrounding the analyzer shall be varied from day to day. One test result for each performance parameter shall be obtained each test day, for seven (7) or fifteen (15) test days as necessary. The tests are performed sequentially in a single procedure.

(3) The 24-hour test day may begin at any clock hour. The first 12 hours out of each test day are required for testing 12-hour zero drift. Tests for the other parameters shall be conducted during the remaining 12 hours.

(d) Table B-4 specifies the line voltage and room temperature to be used for each test day. The line voltage and temperature shall be changed to the specified values at the start of each test day (i.e., at the start of the 12-hour zero test). Initial adjustments (day zero) shall be made at a line voltage of 115 volts (rms) and a room temperature of 25° C.

(5) The test shall be conducted in blocks consisting of 3 test days each until 7 or 15 test results have been obtained. (The final block may contain fewer than three test days.) If a test is interrupted by an occurrence other than a malfunction of the test analyzer, only the block during which the interruption occurred shall be repeated.

(6) During each block, manual adjustments to the electronics, gas, or reagent flows or periodic maintenance shall not be permitted. Automatic adjustments which the test analyzer performs by itself are permitted at any time.

(7) At least 4 hours prior to the start of the first test day of each block, the test analyzer may be adjusted and/or serviced according to the periodic maintenance procedures specified in the manual referred to in § 53.4(b)(3). If a new block is to immediately follow a previous block, such adjustments or servicing may be done immediately after completion of the day's tests for the last day of the previous block and at the voltage and temperature conditions of the first test day.

TABLE B-4—Line voltage and room temperature test conditions

Test day	Line voltage rms	Room temperature °C	Comments
1	115	25	Initial set-up and adjustments.
2	125	20	Adjustments and/or periodic maintenance permitted at end of test.
3	125	20	Adjustments and/or periodic maintenance permitted at end of test.
4	125	20	Adjustments and/or periodic maintenance permitted at end of test.
5	125	20	Adjustments and/or periodic maintenance permitted at end of test.
6	125	20	Adjustments and/or periodic maintenance permitted at end of test.
7	125	20	Examine test results to ascertain if further testing is required.
8	125	20	Adjustments and/or periodic maintenance permitted at end of test.
9	125	20	Adjustments and/or periodic maintenance permitted at end of test.
10	125	20	Adjustments and/or periodic maintenance permitted at end of test.
11	125	20	Adjustments and/or periodic maintenance permitted at end of test.
12	125	20	Adjustments and/or periodic maintenance permitted at end of test.
13	125	20	Adjustments and/or periodic maintenance permitted at end of test.

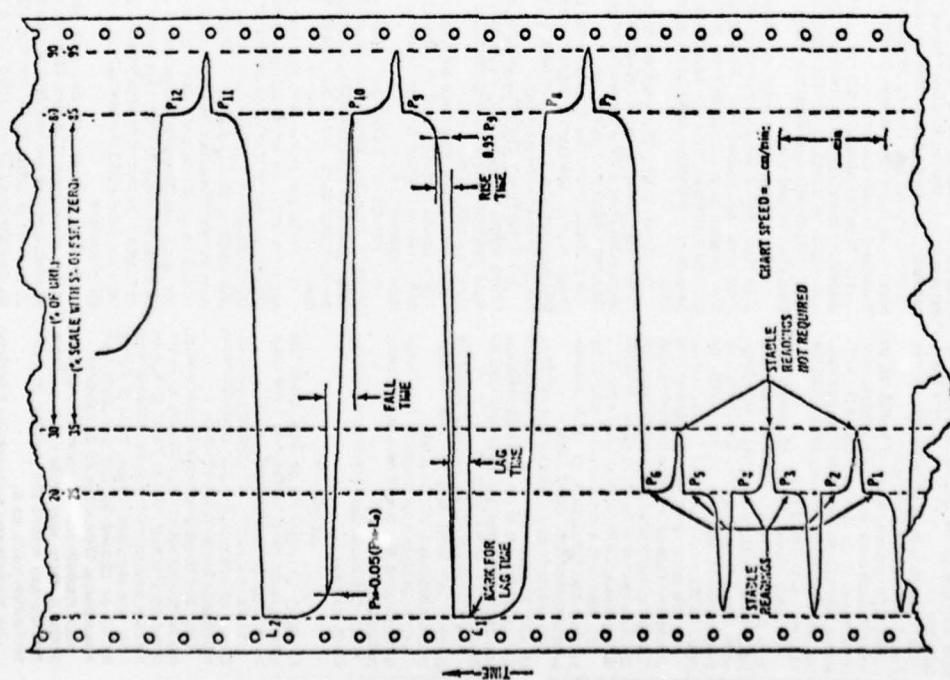
Volts specified shall be controlled to  $\pm 1$  volt.

Temperature specified shall be controlled to  $\pm 1^\circ\text{C}$ .

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**FIGURE B-1.—** Example showing the nature of the tracing obtained during the test for drift, lag time, rise time, fall time, and precision. The time scale has been greatly compressed.

- (ii) For steps (xxv) through (xxxi), a chart speed of at least 10 centimeters per hour shall be used. The actual chart speed, chart speed changes, and time checks shall be clearly marked on the chart.
- (iii) After sufficient time for test analyzer to warm up and stabilize at a line voltage of 115 volts and a room temperature of 25° C. Recalibrate, if necessary, and adjust the zero baseline to 5 percent of chart. No further adjustments shall be made to the analyzer until the end of the tests on the third day.
- (iv) Measure test atmosphere  $A_n$  until a stable reading is obtained, and record this reading (in ppm) as  $Z''_n$ , where  $n=0$  (see Figure B-4 in Appendix A).
- (v) Measure test atmosphere  $A_n$ . Allow for a stable reading and record it as  $M''_n$  where  $n=0$ .
- (vi) Measure test atmosphere  $A_n$ . Allow for a stable reading and record it as  $S''_n$ , where  $n=0$ .
- (vii) The above readings for  $Z''_n$ ,  $M''_n$ , and  $S''_n$  should be taken at least four (4) hours prior to the beginning of test day (1).
- (viii) At the beginning of each test day, adjust the line voltage and room temperature to the values given in Table B-4.
- (ix) Measure test atmosphere  $A_n$  continuously for at least twelve (12) continuous hours during each test day.
- (x) After the 12-hour zero drift test (step ix), sample test atmosphere  $A_n$ . A stable reading is not required.
- (xi) Measure test atmosphere  $A_n$  and record the stable reading (in ppm) as  $P$ . (See Figure B-4 in Appendix A.)
- (xii) Sample test atmosphere  $A_n$ ; a stable reading is not required.
- (xiii) Measure test atmosphere  $A_n$  and record the stable reading as  $P_r$ .
- (xiv) Sample test atmosphere  $A_n$ ; a stable reading is not required.
- (xv) Measure test atmosphere  $A_n$  and record the stable reading as  $P_s$ .
- (xvi) Sample test atmosphere  $A_n$ ; a stable reading is not required.
- (xvii) Measure test atmosphere  $A_n$  and record the stable reading as  $P_{st}$ .
- (xviii) Sample test atmosphere  $A_n$ ; a stable reading is not required.
- (xix) Measure test atmosphere  $A_n$  and record the stable reading as  $P_{st}$ .
- (xx) Sample test atmosphere  $A_n$ ; a stable reading is not required.
- (xxi) Measure test atmosphere  $A_n$  and record the stable reading as  $P_{st}$ .
- (xxii) Sample test atmosphere  $A_n$ ; a stable reading is not required.
- (xxiii) Measure test atmosphere  $A_n$  and record the stable reading as  $P_{st}$ .
- (xxiv) Measure test atmosphere  $A_n$  and record the stable reading as  $P_{st}$ .
- (xxv) Measure test atmosphere  $A_n$ . Record the stable reading as  $L_n$ .
- (xxvi) Sample test atmosphere  $A_n$ ; a stable reading is not required.
- (xxvii) Measure test atmosphere  $A_n$  and record the stable reading as  $P_{st}$ .
- (xxviii) Quickly switch the test analyzer to measure test atmosphere  $A_n$  and mark the recorder chart to show the exact time when the switch occurred.
- (xxix) Measure test atmosphere  $A_n$ . Record the stable reading as  $L_n$ .
- (xxx) Sample test atmosphere  $A_n$ ; a stable reading is not required.
- (xxxi) Measure test atmosphere  $A_n$ . Record the stable reading as  $P_{st}$ .
- (xxxii) Sample test atmosphere  $A_n$ ; a stable reading is not required.
- (xxxiii) Measure test atmosphere  $A_n$  and record the stable reading as  $P_{st}$ .
- (xxxiv) Repeat steps (viii) through (xxxiii) each test day.
- (xxxv) If zero and span adjustments are made after the readings are taken on test days 3, 6, 9, or 12, complete all adjustments, then measure test atmospheres  $A_n$ ,  $A_{st}$ , and  $A_s$ . Allow for a stable reading on each, and record the readings as  $Z''_n$ ,  $S''_n$ , and  $M''_n$ , respectively, where  $n$ =the test day number.
- (19) Determine the results of each day's tests as follows. Mark the recorder chart to show readings and determinations.
- (i) **Zero Drift.** (A) 12-hour. Examine the strip chart pertaining to the 12-hour continuous zero air test. Determine the minimum ( $C_{min}$ ) and maximum ( $C_{max}$ ) readings (in  $\mu\text{m}$ ) during this period of 12 consecutive hours, extrapolating the calibration curve to negative concentration units if necessary. Determine the 12-hour zero drift (12ZD) as  $12ZD = C_{max} - C_{min}$ . (See Figure B-5 in Appendix A.)
- (B) Calculate the 24-hour zero drift (24ZD) for the  $n$ -th test day as  $24 ZD = Z_n - Z_{n-1}$ , or  $24ZD = Z_n - Z_{n-1}$  if zero adjustment was made on the previous day, where  $Z_n = 1/2(L_n + L_{n-1})$  for  $L_n$  and  $L_{n-1}$  taken on the  $n$ -th test day.
- (C) Compare 12ZD and 24ZD to the zero drift specification in Table B-1. Both 12ZD and 24ZD must be equal to or less

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#### App. A

than the specified value to pass the test for zero drift.

(ii) Span Drift

(A) Span drift at 20 percent of URL (MSD):

$$MSD_n = \frac{M_n - M_{n-1}}{M_{n-1}} \times 100\%$$

or

$$MSD_n = \frac{M_n - M'_{n-1}}{M'_{n-1}} \times 100\%$$

If span adjustment was made on the previous day, where

$$M_n = \frac{1}{6} \sum_{i=1}^6 P_i$$

(C) Both  $P_n$  and  $P_{n-1}$  must be equal to or less than the specification given in Table B-1 to pass the test for precision.

APPENDIX A—OPTIONAL FORMS FOR REPORTING TEST RESULTS

#### Table B-6. SYMBOLS AND ABBREVIATIONS

$S_n$  ..... Analyzer reading at specified

$S_{n-1}$  ..... Analyzer reading at 0 concentration for LDL test.

Digital meter.

DM ..... Maximum analyzer reading during 12ZD test.

Gain ..... Minimum analyzer reading during 12ZD test.

$I_n$  ..... Subscript indicating the  $n$ -th quantity in a series.

Interference equivalent.

IR ..... First analyzer zero reading for 24ZD test.

$I_n$  ..... Second analyzer zero reading for 24ZD test.

M ..... Average of  $P_1, \dots, P_6$  for the  $n$ -th test day.

MSD ..... Adjusted span reading at 20 percent of URL on the  $n$ -th test day.

Span drift at 20 percent of URL.

$S_n$  ..... Subscript indicating the test day number.

P ..... Analyzer reading for precision test.

$P_n$  ..... The  $n$ -th analyzer reading for precision test.

Precision at 20 percent of URL.

Precision at 80 percent of URL.

Analyzer reading of pollutant alone for IR test.

Analyzer reading with interferent added for IR test.

The  $i$ -th DM reading for noise test.

Standard deviation of noise readings.

$S_n$  ..... Noise value ( $S$ ) measured at 0 concentration.

$S_n$  ..... Noise value ( $S$ ) measured at 80 percent of URL.

#### App. A

Average of  $P_1, \dots, P_6$  for the  $n$ -th test day.

Adjusted span reading at 80 percent of URL on the  $n$ -th test day.

Percent of URL on the  $n$ -th test day.

Upper range limit.

Span drift at 80 percent of URL.

Upper range limit.

Span drift at 80 percent of URL.

Upper range limit.

Span drift at 80 percent of URL.

Upper range limit.

Span drift at 80 percent of URL.

Upper range limit.

Span drift at 80 percent of URL.

Upper range limit.

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**Chapter I—Environmental Protection Agency**

**“Title 40—Protection of Environment**

**App A**

TEST NUMBER	TEST PROJECT	TESTS IN CALCULATION	TEST DATA											
			1	2	3	4	5	6	7	8	9	10	11	12
1	LEL0 DETERMINATION	$\frac{R_1}{R_0}$												
2	LEL0 DETERMINATION	$\frac{R_2}{R_0}$												
3	LEL0 DETERMINATION	$\frac{R_3}{R_0}$												
4	LEL0 DETERMINATION	$\frac{R_4}{R_0}$												
5	LEL0 DETERMINATION	$\frac{R_5}{R_0}$												
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115	LEL0 DETERMINATION	<												



## Chapter I—Environmental Protection Agency

### Title 40—Protection of Environment

#### § 53.32

Ulfed, dated, signed by the analyst performing the test, and submitted.

(e) Sample Manifold. All test concentration measurements shall be made on air sampled from a common intake and distribution manifold, and in such a way that both the candidate method and the reference method receive homogeneous air samples. Precautions shall be taken in the design and construction of this manifold to minimize the removal of particulates and trace gases, and to insure that identical samples reach the two methods. Schematic drawings, physical illustrations, descriptions, and complete details of this manifold system shall be submitted.

140 FR 7049, Feb. 18, 1975, as amended at 40 FR 18169, Apr. 25, 1975]

#### § 53.31 Test conditions.

(a) All Methods. All test measurements made or test samples collected shall be at a room temperature between 20° and 30° C., and at a line voltage between 105 and 125 volts. All methods shall be calibrated as specified in paragraph (c) of this section prior to initiation of the tests.

(b) Automated Methods. Set-up and start-up of the test analyzer (and the reference method if automated) shall be in strict accordance with the applicable operation manual(s). If the test analyzer does not have an integral strip chart recorder, connect the analyzer output to a suitable strip chart recorder of the servo, null-balance type. This recorder shall have a chart width of at least 25 centimeters, a response time of 1 second or less, a deadband of not more than 0.25 percent of full scale, and capability of either reading measurements at least 5 percent below zero or offsetting the zero by at least 5 percent.

**Note.**—Other data acquisition components may be used along with the chart recorder during the conduct of these tests. Use of the chart recorder is intended only to facilitate evaluation of data submitted.

Allow adequate warmup or stabilization time as indicated in the applicable operation manual(s) before beginning the tests.

(c) Calibration. The reference method shall be calibrated according to the applicable calibration procedure manual (or portion thereof) which the test analyzer performs by itself are permitted at any time. At 4-day intervals, a part of the method. For a candidate automated method, the test analyzer only adjustments and periodic mainte-

nance as specified in the manual referred to in § 53.4(b)(3) are permitted. The candidate method passes the test for consistent relationship.

(d) All test measurements shall be made with the same test analyzer; use of multiple test analyzers is not permitted. The test analyzer shall be operated continuously during the entire period of the test measurements.

(3) If a test analyzer should malfunction during any of these tests, the entire set of measurements shall be repeated, and a detailed explanation of the malfunction, remedial action taken, and whether recalibration was necessary (along with all pertinent records and charts) shall be submitted.

140 FR 7049, Feb. 18, 1975, as amended at 40 FR 18169, Apr. 25, 1975]

#### § 53.32 Test procedures.

(a) Conduct the first set of simultaneous measurements with the candidate and reference methods:

(1) Table C-1 specifies the type (1- or 24-hour) and number of measurements to be made in each of the three test concentration ranges.

(2) The pollutant concentration must fall within the specified range as measured by the reference method.

(3) The measurements shall be made in the sequence specified in Table C-2, except for the 1-hour SO<sub>2</sub> measurement, which are all in the high range.

(b) For each pair of measurements, determine the difference (discrepancy) between the candidate method measurement and reference method measurement. A discrepancy which exceeds the discrepancy specified in Table C-1 constitutes a failure. (See Figure C-1 in Appendix A for a suggested format for reporting the test results).

(c) The results of the first set of measurements shall be interpreted as follows:

(1) Zero (0) failures: The candidate method passes the test for consistent relationship.

(2) Three (3) or more failures: The candidate method fails the test for consistent relationship.

(3) One (1) or two (2) failures: Conduct a second set of simultaneous measurements as specified in Table C-1. The results of the combined total of first-set and second-set measurements shall be interpreted as follows:

(a) For applicable methods, control or calibration checks may be performed once per day without adjusting the test analyzer or method. These checks may be used as a basis for a linear interpolation-type correction to be applied to the measurements to correct for drift. If such a correction is used, it shall be applied to all measurements made with the method, and the correction procedure shall become a part of the method.

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53.32

TABLE C-1. TEST CONCENTRATION RANGE, NUMBER OF MEASUREMENTS REQUIRED, AND MATRIX DISCHARGE SPECIFICATION

Pollutant	Concentration range P/M	Simultaneous measurements required				Maximum discrepancy specifications P/M
		1 hr	24 hr	First set	Second set	
Ozone	Low 0.05-0.10 Medium 0.15-0.25 High 0.35-0.45	6	6	6	6	0.02
Total	Low 7-11 Medium 20-30 High 30-45	14	18	6	6	.04
Carbon monoxide	Low 0.05-0.15 Medium 0.30-0.50 High 0.30-0.50	14	14	6	6	1.3
Total	Low 0.05-0.15 Medium 0.30-0.50 High 0.30-0.50	14	14	6	6	2.0
Sulfur dioxide	Low 0.05-0.15 Medium 0.30-0.50 High 0.30-0.50	7	8	2	2	.02
Total	Low 0.05-0.15 Medium 0.30-0.50 High 0.30-0.50	7	8	2	2	.04

TABLE C-2. SEQUENCE OF TEST REQUIREMENTS

Measurement	Concentration range	Second set	
		First set	Second set
High	Low	Medium	Medium
Medium	High	High	Low
Low	Medium	Medium	Medium
Medium	Low	Low	Low
High	Medium	Medium	Medium
Medium	High	High	High
Low	Medium	Medium	Medium
Medium	Low	Low	Low
High	High	High	High
Medium	Medium	Medium	Medium
Low	Low	Low	Low

## App. A

### Title 40—Protection of Environment

#### **APPENDIX A—OPTIONAL FORM FOR REPORTING TEST RESULTS**

II o

Figure C-1. Form for Subpart C test results.

[40 FR 7049, Feb. 18, 1975, as amended at 40 FR 18169, Apr. 25, 1975]

APPENDIX III

GUIDELINE FOR PUBLIC REPORTING  
OF DAILY AIR QUALITY

Waste Management, and Planning and Management. The guideline was prepared by the EPA Working Group to Develop an Air Quality Index in response to a request from the Federal Interagency Task Force on Air Quality Indicators of which EPA is a member. The Federal Task Force, chaired by the Council on Environmental Quality, was created as a result of a joint EPA/CEQ report<sup>1</sup> which pointed out existing problems resulting from the present diversity of indices used in the United States and Canada.

This guideline suggests the use of the Pollutant Standards Index (PSI) for those local and state air pollution control agencies wishing to report an air quality index on a daily basis. The PSI places maximum emphasis on protecting the public health; that is, it advises the public of any possible adverse health effects due to pollution. In order to err on the side of public safety, the index stresses reporting on the basis of the stations with the highest pollutant concentrations and assumes that other unsampled portions of the community will also experience high concentrations. In addition, its emphasis is upon acute health effects occurring over very short time periods (24 hours or less) rather than chronic effects occurring over months or years. It is not intended for, and should not be used for, ranking urban areas in terms of the severity of their air pollution problems. Such rankings require the use of many other kinds of environmental data not incorporated in this index.

Finally, Appendix A discusses the meteorological information needs of forecasting relative index changes. This was prepared by personnel from the National Oceanic and Atmospheric Administration.

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**ENVIRONMENTAL PROTECTION  
AGENCY**  
[FRL 610-6]  
**GUIDELINE FOR PUBLIC REPORTING  
OF DAILY AIR QUALITY**  
Pollutant Standards Index (PSI)  
(OAQPS Number 1.2-044)  
PREPARED BY  
EPA WORKING GROUP TO DEVELOP AN AIR  
QUALITY INDEX  
CONTRIBUTING AGENCIES: U.S. ENVIRON-  
MENTAL PROTECTION AGENCY, OFFICE OF  
RESEARCH AND DEVELOPMENT, OFFICE OF  
AIR AND WASTE MANAGEMENT, OFFICE OF  
PLANNING AND MANAGEMENT  
NATIONAL OCEANIC AND ATMOSPHERIC  
ADMINISTRATION—AUGUST, 1976  
The U.S. Environmental Protection Agency's recommended "Pollutant Standards Index" (PSI) is the result of a joint effort on the part of EPA's Offices of Research and Development, Air and

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1. EXECUTIVE SUMMARY

This guideline suggests the use of the Pollutant Standards Index (PSI) for those local and state air pollution control agencies wishing to report an air quality index on a daily basis. The document also includes appropriate monitoring and re-

porting guidance. The guideline is the result of an earlier study<sup>1</sup> showing that of all the air quality indices in use today, no two are exactly the same. A potentially serious problem of public confusion can occur in regions where neighboring states and cities use different indices. The PSI

See footnotes, p. 37669.

## NOTICES

also responds to the request of several state and local agencies that the U.S. Environmental Protection Agency provide them with a recommended uniform air quality index.

The recommended index incorporates five pollutants—carbon monoxide, sulfur dioxide, total suspended particulate, photochemical oxidants, and nitrogen dioxide—for which there are short-term (24 hours or less) health-related National Ambient Air Quality Standards (NAAQS),<sup>1</sup> and/or Federal Episode Criteria,<sup>2,3</sup> and Significant Harm Levels.<sup>4,5</sup> A sixth variable—the product of total suspended particulate and sulfur dioxide—is computed and is included in the index equation. This variable and also nitrogen dioxide are treated differently than the other pollutants because they have no short-term NAAQS. Therefore, they are reported when they exceed the Federal Episode Criteria and Significant Harm Levels. Because of the basic design of the index, any further pollutant requiring NAAQS, Federal Episode Criteria, and Significant Harm Levels can be readily added.

The index uses a "segmented linear function"<sup>6</sup> to convert each air pollutant concentration into a normalized number. The NAAQS for each pollutant corresponds to  $PSI=100$ , and the Significant Harm Level corresponds to  $PSI=500$ .

At a minimum, PSI reports that pollutant with the highest index value of all the pollutants being monitored, a dimensionless number, and a descriptor word. On days when two or more pollutants violate their respective NAAQS, each of the pollutants should be reported. Five descriptor words have been chosen to characterize daily air quality: "good," "moderate," "unhealthful," "very unhealthful," and "hazardous." In addition, for each descriptor word, generalized health effects and cautionary statements are provided for use when the air is characterized as "unhealthful" or worse.

For large metropolitan areas comprised of many smaller cities and suburbs where significant air quality differences may exist, the air pollution control agency may wish to report separate index values for each community. This has the advantage of showing the public how air pollution varies over the larger metropolitan area. The pollutants would be monitored at population-oriented locations where the maximum concentration for the particular pollutant is expected to occur, and the public within each community would be made aware of the worst air quality to which it is exposed.

Further guidance is given on the measurements practices and monitor siting considerations (Section 5).

PSI should not be used to rank cities. An evaluation of PSI in eight cities<sup>7,8</sup> illustrated the difficulties of attempting to compare air quality levels in different cities using this or any other index. PSI

<sup>1</sup> A segmented linear function consists of two or more straight lines, drawn between successive coordinates ("breakpoints") where each line may have a different slope.

See footnotes, p. 37669.

is designed for the daily reporting of air quality to advise the public of potentially acute, but not chronic health effects. To properly rank the air pollution problems in different cities, one should rely not just on air quality data, but should include all data on population characteristics, daily population mobility, transportation patterns, industrial composition, emission inventories, meteorological factors, and the spatial representativeness of air monitoring sites. A correct ranking should also consider the number of people actually exposed to various concentrations, as well as the frequency and duration of their exposure.

Adoption of PSI should reduce the confusion due to the existence of many indices. PSI has several advantages: (1) it is simple and can be easily understood by the public, (2) it can accommodate new pollutants, (3) it is based on a reasonable scientific premise, (4) it relates to NAAQS, Federal Episode Criteria, and Significant Harm Levels, (5) it exhibits day-to-day variations, and (6) a qualitative trend in the index can be forecast for periods up to a day in advance, especially during episodic conditions.

## 2. INTRODUCTION

A major area of concern in the field of air pollution control is how to best report daily air quality to the public. A recent CEQ/EPA Report<sup>9</sup> indicates that of the 55 largest U.S. metropolitan air pollution control agencies, 33 use an air pollution index. In addition, five states and two Canadian Provinces operate state-wide (or Province-wide) index systems. With two minor exceptions, no two indices were found to be exactly the same. The public confusion generated by the use of so many indices is particularly evident in bordering states using different indices. Therefore, there is a need to develop a uniform index to report the daily status of air pollution.

A recent paper<sup>10</sup> emphasizes the need for a truly meaningful index to have a sound scientific basis. The paper suggests that such an index be based on the relationship between pollutant concentration and adverse health (welfare) effects—that is, a "damage function." Unfortunately, it is an extremely complex undertaking to relate measured air pollutant concentrations to the many diverse effects of air pollution—for example, aggravation of disease in susceptible people, increased incidence of respiratory illness in healthy persons, impairment of human motor function, reduced visibility, corrosion of materials, and soiling of buildings. Arriving at an air quality standard for a given pollutant—which is just one point in a damage function—has required vast quantities of data, medical advisory committees, detailed epidemiological studies, and other extensive research. The air quality criteria documents published for the major air pollutants<sup>10-14</sup> reflect the complexity of the process.

The recent paper<sup>10</sup> also emphasizes the importance of an index accounting for the adverse effects associated with com-

bination of pollutants—that is, synergism. For example, the criteria document on sulfur oxides<sup>11</sup> states that adverse health effects attributable to sulfur oxides are intensified in the presence of particulate matter. Understanding synergistic effects adds greatly to the problem of obtaining a truly meaningful air quality index. These problems stress the need for additional research to develop pollutant-related damage functions that take into account synergistic effects on health and welfare.

As an interim solution to these problems, this guideline recommends a uniform index to report daily air quality, along with appropriate monitoring guidance. This index will serve until a more meaningful air quality index can be created. If adopted, a uniform index should end the confusion associated with the use of many varied indices.

## 3. THE EPA RECOMMENDED DAILY INDICATOR—POLLUTANT STANDARDS INDEX (PSI)

The Pollutant Standards Index (PSI or  $\psi$ ) is the result of a joint effort by EPA's Offices of: Research and Development, Air and Waste Management, and Planning and Management. Its evolution has included formulation of several candidate index structures,<sup>15,16</sup> and the index has undergone an extensive review process involving state and local air pollution control agencies, public organizations, and media representatives.

The recent CEQ/EPA compendium of air pollution indices<sup>1</sup> developed an "index classification system" to analyze and compare the various indices used by state, Provincial, and local agencies. Indices were categorized according to four criteria: (1) number of pollutant variables measured, (2) calculation method used to compute the index, (3) descriptor categories reported with the index, (4) method of reporting (whether it is "combined," "maximum," or "individual").

The report found that the greatest number of the indices in use<sup>1</sup> incorporate five of the six National Ambient Air Quality Standards (NAAQS) pollutants (hydrocarbons are excluded because there are no direct health effects associated with the pollutant). It is controlled because it is a precursor to the formation of photochemical oxidants); (2) use a segmented linear function<sup>6</sup>; (3) are based on the maximum of one of the pollutant variables; and (4) use three to five descriptor categories.

In the following sections, the structure of PSI is presented according to the "index classification system" categories.

## 3.1 Number of pollutants

PSI includes five pollutants: carbon monoxide (CO), sulfur dioxide ( $SO_2$ ), total suspended particulate matter (TSP), photochemical oxidant ( $O_3$ ) and nitrogen dioxide ( $NO_2$ ). Primary (that is,

<sup>10</sup> A segmented linear function consists of two or more straight lines, drawn between successive coordinates ("breakpoints") where each line may have a different slope.

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health related) NAAQS, and/or Federal Episode Criteria, and Significant Harm Levels exist for all five. In addition, one pollutant product TSP $\times$ SO<sub>2</sub> is included because it has both Federal Episode Criteria and a Significant Harm Level.<sup>a</sup> As with NO<sub>x</sub>, which has no short-term primary NAAQS, the product is reported when the Federal Episode or Significant Harm Levels are exceeded. Finally, because of the structure of the index, any pollutant identified in the future for which NAAQS, Federal Episode Criteria, and Significant Harm Levels are adopted can be added without modifying the basic form of the index.

## 3.2 Calculation method

A segmented linear function is used relating actual air pollution concentrations to a normalized number. For example, PSI ( $\psi$ ) equals 100 when the NAAQS for each pollutant is reached, while ( $\psi$ ) equals 500 when the Significant Harm Level for each pollutant is reached. The normalized number should be easier for the general public to understand because it does not require one to know specific NAAQS concentrations or the many different Federal Episode and Significant Harm Levels.

The index breakpoints are listed in metric units (Table 1) and in parts per million (Table 2). The first breakpoint separates the descriptor categories "good" and "moderate." For CO and O<sub>3</sub>, the first breakpoint was chosen at 50 percent of the primary NAAQSs. In the case of TSP and SO<sub>2</sub>, concentrations equal to their respective primary annual NAAQS were chosen because the frequent occurrence of values greater than these concentrations could lead to violations of their respective annual NAAQS. In an area where a violation of either the annual primary TSP or SO<sub>2</sub> standard occurs, approximately 50 percent or more of the days will thus be classified as "moderate" or worse. This approach minimizes the potential for public confusion which might arise from a preponderance of days reported as "good," followed by the report that the annual health-related standards has been violated.

The breakpoints between the primary NAAQS and Significant Harm Levels are somewhat arbitrarily set at the Federal Episode Alert, Warning, and Emergency Levels, except for oxidants. In the case of oxidant, 400  $\mu\text{g}/\text{m}^3$  was used as the PSI breakpoint for the descriptor words "unhealthful" and "very unhealthful" because it appears to be more consistent with the descriptor words than the suggested administrative Alert level of 200  $\mu\text{g}/\text{m}^3$ .<sup>\*\*</sup>

<sup>\*\*</sup> Several air pollution control agencies are using 400  $\mu\text{g}/\text{m}^3$  instead of 200  $\mu\text{g}/\text{m}^3$  as their Alert level with concurrence by the Environmental Protection Agency.

See footnotes, p. 37669.

TABLE 1. Breakpoints for PSI ( $\psi$ ) in Metric Units

Breakpoints	PSI Value ( $\psi$ )	TSP $\mu\text{g}/\text{m}^3$ 24-hr.	SO <sub>2</sub> $\mu\text{g}/\text{m}^3$ 24-hr.	TSP $\times$ SO <sub>2</sub> ( $\mu\text{g}/\text{m}^3$ ) <sup>2</sup>	CO $\mu\text{g}/\text{m}^3$ 8 hours	O <sub>3</sub> $\mu\text{g}/\text{m}^3$ 1-hr.	NO <sub>2</sub> $\mu\text{g}/\text{m}^3$ 1-hr.
50% of primary short-term NAAQS	50	75 <sup>a</sup>	80 <sup>a</sup>	b	5.0	80	b
Primary short-term NAAQS	100	260	365	b	10.0	160	b
Alert Level	200	375	800	65x10 <sup>3</sup>	17.0	400 <sup>c</sup>	1130
Warning Level	300	625	1600	261x10 <sup>3</sup>	34.0	800	2260
Emergency Level	400	875	2100	393x10 <sup>3</sup>	46.0	1000	3000
Significant Harm Level	500	1000	2620	490x10 <sup>3</sup>	57.5	1200	3750

<sup>a</sup>Annual primary NAAQS.

<sup>b</sup>No index value reported at concentration levels below those specified by the Alert level criteria.

<sup>c</sup>For the PSI index 400  $\mu\text{g}/\text{m}^3$  appears to be a more consistent breakpoint between the descriptor words "unhealthful" and "very unhealthful" than the O<sub>3</sub> Alert Level of 200  $\mu\text{g}/\text{m}^3$ .

TABLE 2. Breakpoints for PSI ( $\psi$ ) in Parts Per Million

Breakpoints	PSI Value ( $\psi$ )	SO <sub>2</sub> 24-hr.	TSP $\times$ SO <sub>2</sub> ( $\mu\text{g}/\text{m}^3 \times \text{ppm}$ )	CO 8 hours	O <sub>3</sub> 1-hr.	NO <sub>2</sub> 1-hr.
50% of primary NAAQS	50	.03 <sup>a</sup>	b	1.5	0.04	b
Primary NAAQS	100	.14	b	9.0	0.08	b
Alert Level	200	.30	22.727	15.0	0.20 <sup>c</sup>	0.60
Warning Level	300	.60	91.259	30.0	0.40	1.20
Emergency Level	400	.80	137.413	40.0	0.50	1.60
Significant Harm Level	500	1.00	171.329	50.0	0.60	2.00

<sup>a</sup>Annual primary NAAQS.

<sup>b</sup>No index value reported at concentration levels below those specified by the Alert Level criteria.

<sup>c</sup>For the PSI index 0.2 ppm appears to be a more consistent breakpoint between the descriptor words "unhealthful" and "very unhealthful" than the O<sub>3</sub> Alert Level of 0.1 ppm.

Figures 1 through 5 show the segmented linear function for each of the NAAQS pollutants, and Figure 6 shows the function for the product of TSP and SO<sub>2</sub>. If NAAQS for new pollutants are adopted in the future, they can be accommodated by drawing a new segmented linear function.

## 3.3 Descriptor categories

PSI is primarily a health related index as shown by the descriptor words: "good," "moderate," "unhealthful," "very unhealthful," and "hazardous." (Table 3).

The breakpoints used to separate these descriptor words are somewhat arbitrary. On the basis of health effects data above, it is not possible to establish a sharp demarcation between any two descriptor words. However, when the five pollutants were examined in the context of severity of health effects, their NAAQS and EPA suggested administrative Alert, Warning, and Emergency levels tended to provide convenient breakpoints, except for the oxidant Alert level, which was replaced with 400  $\mu\text{g}/\text{m}^3$ , as discussed earlier.

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TABLE 2. COMPARISON OF PSI VALUES WITH POLLUTANT CONCENTRATIONS, DESCRIPTOR WORDS  
GENERALIZED HEALTH EFFECTS, AND CAUTIONARY STATEMENTS

INDEX VALUE	AIR QUALITY LEVEL	POLLUTANT LEVELS					GENERAL HEALTH EFFECT <sup>a</sup>	CAUTIONARY STATEMENTS
		TSP (24-hr avg), µg/m <sup>3</sup>	SO <sub>2</sub> , (24-hr avg), µg/m <sup>3</sup>	CO, (8-hr avg), mg/m <sup>3</sup>	O <sub>3</sub> , (1 hr avg), ppm	NO <sub>2</sub> , (1 hr avg), ppm		
400	SIGNIFICANT HARM	1000	20/20	87.5	—1200	—2750	HAZARDOUS	Prevents death of II and elderly. Healthy people will experience severe symptoms that effect their normal activity.
400	EMERGENCY	87.5	—21/09	48.9	—1000	—2000	HAZARDOUS	Prevention of certain disease in addition to significant depression of symptoms and decreased exercise tolerance in healthy persons.
300	WARNING	625	—18/03	34.0	—800	—2250	VERY UNHEALTHFUL	Significant depression of symptoms and decreased exercise tolerance in persons with heart or lung disease, and reduced physical activity.
300	ALERT	375	—803	17.0	—400 <sup>b</sup>	—1130	UNHEALTHFUL	Mild aggression of symptoms in susceptible persons, with irritant symptoms in the healthy population.
100	RAAC <sup>c</sup>	200	—20/5	10.0	—160	—	MILD	Persons with existing heart or respiratory ailments should reduce physical exertion and decrease activity.
100	80% OF RAAC	75 <sup>d</sup>	—10/5	8.0	—80	—	MODERATE	
100	50% OF RAAC	50 <sup>d</sup>	—5/5	5.0	—50	—	SEVERE	
100	25% OF RAAC	25 <sup>d</sup>	—2.5/2.5	2.5	—25	—	EXTREME	

<sup>a</sup>The index values reported at concentrations levels below those specified by "Alert Level" criteria.  
<sup>b</sup>Second primary RAACs.  
<sup>c</sup>4000 µg/m<sup>3</sup> was instead of the O<sub>3</sub> Alert Level of 200 µg/m<sup>3</sup> (see text).

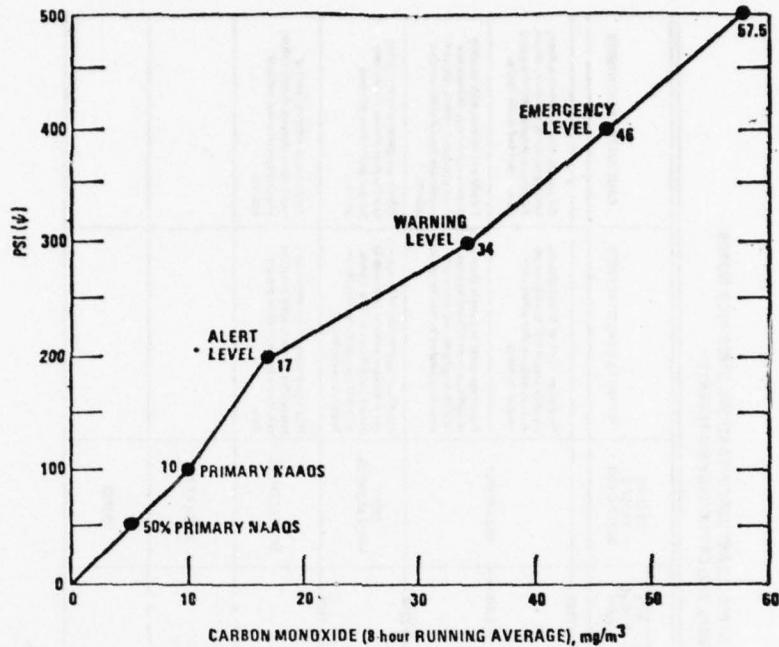


Figure 1. PSI function for carbon monoxide

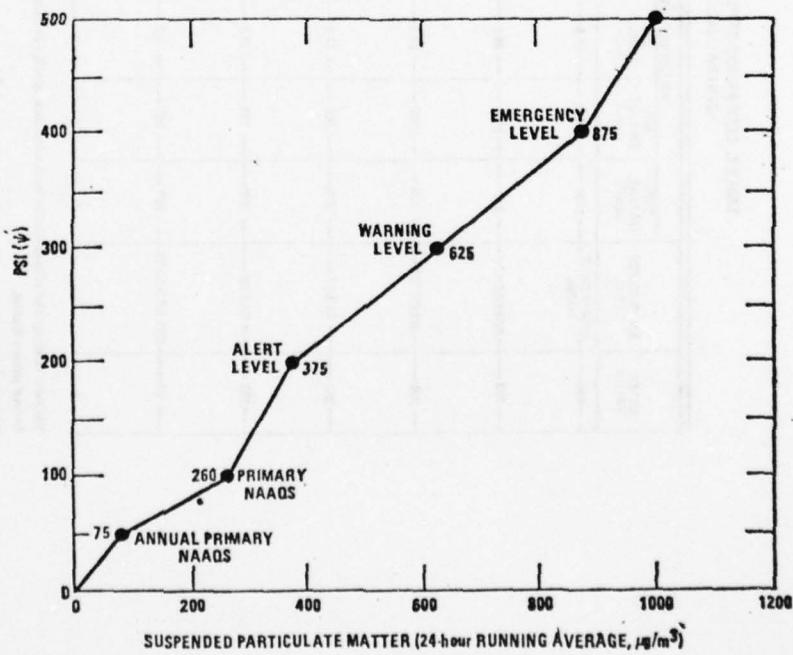


Figure 2. PSI function for suspended particulate matter

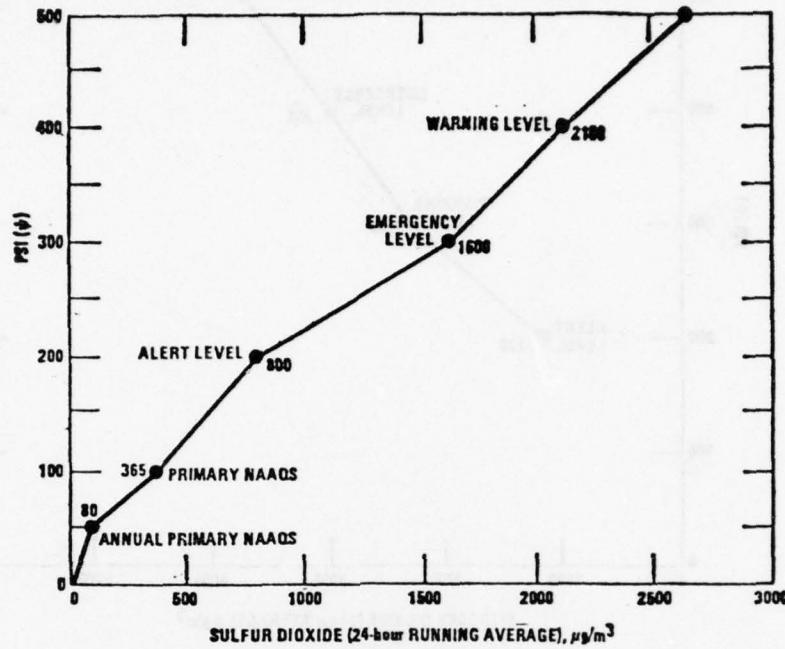


Figure 3. PSI function for sulfur dioxide

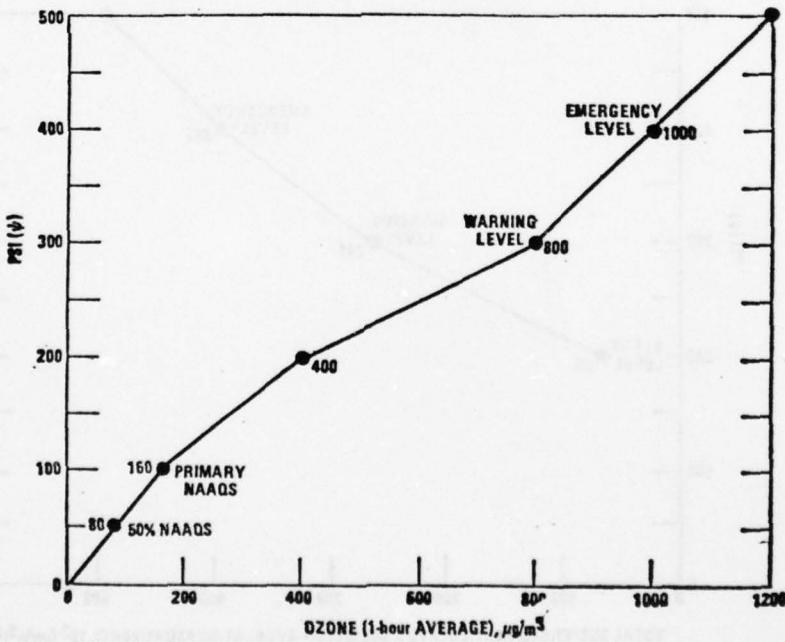


Figure 4. PSI function for photochemical ozone

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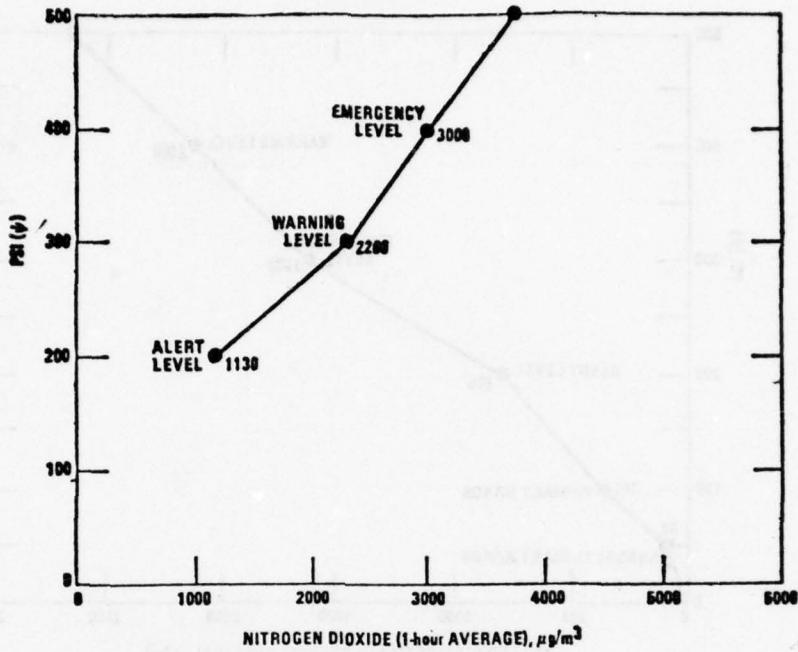


Figure 5. PSI function for nitrogen dioxide.

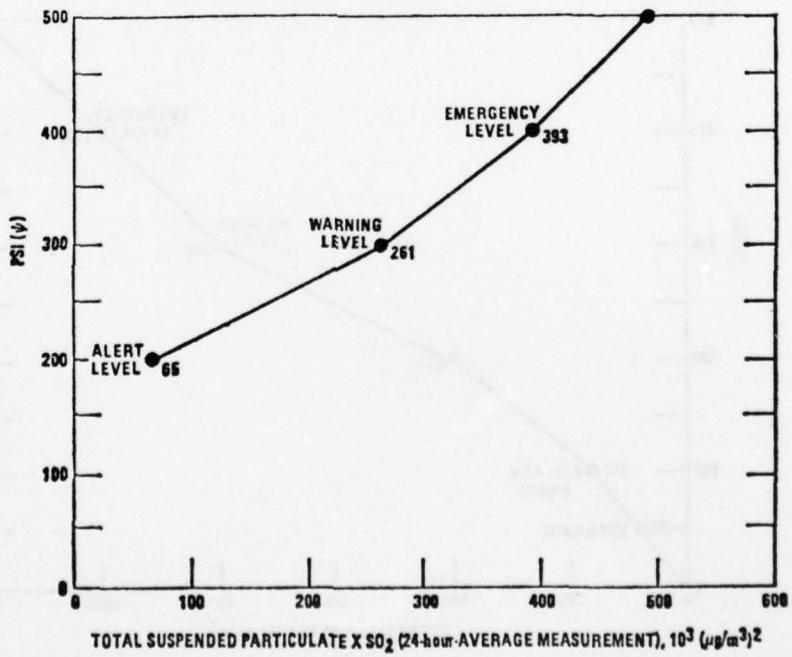


Figure 6. PSI function for product of total suspended particulate and sulfur dioxide

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Air pollution levels between the short-term primary NAAQS and the Alert level for TSP, SO<sub>2</sub>, and CO and 400 µg/m<sup>3</sup> for O<sub>3</sub> are deemed "unhealthful," because mild aggravation of respiratory symptoms in susceptible persons and irritation symptoms in the healthy population occur at some point above the short-term primary NAAQS and at and below the Alert levels for TSP, SO<sub>2</sub>, and CO and 400 µg/m<sup>3</sup> for O<sub>3</sub>.<sup>12</sup> NO<sub>x</sub> is not reported until concentrations exceed the Alert level because no short-term NAAQS has been established.<sup>13</sup> Air pollution concentrations above the Alert level but below the Warning level are classified as "very unhealthful," while concentrations above the Warning level are "hazardous."

These classifications are related to generalized health effects and appropriate cautionary statements (Table 3).<sup>14</sup> A single set of generalized health effects and cautionary statements is indicated for the descriptor words "unhealthful" and "very unhealthful." The "hazardous" category has two sets of generalized health effects and cautionary statements. The first set is reported when the index exceeds 300 and the second when the index exceeds 400 indicating the increasing severity of the air pollution levels.

In the case of TSP and SO<sub>2</sub>, short-term secondary air quality standards also exist below their primary NAAQS. Secondary standards are designed to protect against the adverse effects of pollution on the public welfare (animals, vegetation, materials, visibility, etc.). According to PSI, if their short term secondary NAAQSs are violated, the concentrations would be classified as "moderate" or worse. While this descriptor word is valid from a health viewpoint, the air quality is unsatisfactory from the standpoint of welfare effects. Because PSI is a health-related index, the user may wish to report on the possible welfare effects when either the short term TSP or SO<sub>2</sub> NAAQS is violated.

## 4. REPORTING PROCEDURES

PSI has been designed to be as flexible as possible in allowing air pollution control agencies to decide for themselves the information to include in their reports to the various media. This section examines the recommended method of reporting the index, the reporting of the Federal Episode Criteria, and the concept of flexible media reporting.

## 4.1 Reporting the index

Since each pollutant is examined separately by comparing its measured concentration with the NAAQS, the Episode Levels, and the Significant Harm Level, each pollutant can be reported separately. At the minimum, the pollutant with the highest index value should be reported to advise the public of the worst air pollution to which it is exposed. On days when two or more pollutants violate their respective NAAQS—that is, have PSI values greater than 100—then each of the pollutants should be reported. The index values of the other pollutants may also be reported for completeness. When the air pollution level is reported as "un-

healthful," "very unhealthful," or "hazardous," cautionary statements should also be used. In addition, the generalized health effects can be used.

Users of PSI may wish to report on the health effects of each pollutant individually, thereby providing more detailed language on each pollutant than is available in Table 3. In preparing such information for the public, the user is encouraged to seek appropriate medical advice and to consult the literature.<sup>15</sup>

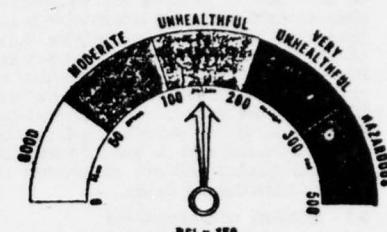
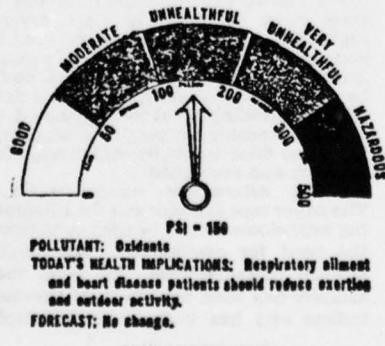
## 4.2 Reporting the Federal episode criteria

When the Federal Episode Levels for each pollutant are exceeded, the user should report the administrative actions associated with the Alert, Warning, or Emergency Levels. The issuance of administrative actions depends, of course, upon the forecast of meteorological conditions affecting future pollution levels.

Issuance of administrative actions also apply to the product of TSP and SO<sub>2</sub>, which has both Federal Episode Criteria and Significant Harm Levels.<sup>16</sup> Although available health effects information has not been codified to tie the descriptor words to the product of TSP and SO<sub>2</sub>, the product is included for purposes of administrative completeness.

## 4.3 Forecasting the index

The forecasting of a quantitative index for periods up to a day in advance would be difficult without extensive meteorological data and specialized expertise that some air pollution control agencies may not possess. However, qualitative index forecasting is practicable using the National Weather Service's Air Pollution Weather Forecast Program.<sup>17</sup> With this weather information, along with available emissions and air quality trend data, agencies can develop techniques or procedures to forecast the relative change in the index by using the following word descriptors: No significant change, decrease, or increase. The principal responsibility for obtaining the necessary emission and air quality information lies with the air pollution control agency using the index. The air pollution control agency would integrate the meteorological information and apply the predictive methods to generate the forecast. The information needs for forecasting relative index changes is discussed further in Appendix A.



POLLUTANT: Oxidants  
TODAY'S HEALTH IMPLICATIONS: Respiratory ailment and heart disease patients should reduce exertion and outdoor activity.  
FORECAST: No change.

## 4.4 Flexible media reporting

The index has been designed to be as flexible as possible in reporting the status of air quality to the public. Either short or long reports can be used. For television, the report could read, "Today the air pollution index is 50, the air quality is good." However, when the air pollution becomes unhealthy, then several possible reports could be considered for television, the news media, or telephone recordings. For example, when oxidant pollution reaches a concentration of 280 µg/m<sup>3</sup> (0.14 ppm), the report could take several different forms.

(1) Today, the air pollution index is 150. The air is "unhealthful." The pollutant O<sub>3</sub> is responsible.

(2) An air pollution alert has (or has not) been called based on the forecast for the remainder of the day (and/or) tomorrow.

(3) Repeat the above and add the following cautionary statements: "Persons with existing heart or respiratory ailments should reduce physical exertion and outdoor activity."

(4) The report could include everything said in (1), (2), and (3) and then add that "unhealthful" air can cause "mild aggravation of symptoms in susceptible persons, with irritation symptoms in the healthy population."

(5) Finally, the report could conclude with the forecast of tomorrow's air pollution level, such as "no change in the air pollution level is expected."

Table 3 should be referred to in preparing the air pollution status report to the public. Figures 7 and 8 illustrate the above ozone example by showing possible reports for the television and newspaper, respectively. Both figures provide essential information, indicating the PSI value, the critical pollutant, the health implications for the public, and the next day's forecast. Each of the descriptor categories has been given equal weight. The information is displayed so that it can be presented as rapidly as possible in an easy-to-understand format.

## 5. MONITORING REQUIREMENTS

## 5.1 Need for monitoring uniformity

In order for PSI to be readily accepted, the data used in calculating the index must be comparable from site to site within a region. Since these data are to

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be obtained at existing air monitoring sites, certain easily implementable practices can eliminate considerable variability in the data. Among these are using: (1) uniformity of site types—that is, residential, commercial, etc.; (2) Federal Reference Methods or their equivalent; (3) standardizing sampling height and probe exposure; and (4) good housekeeping and quality control procedures to provide high quality data.

### 5.2 Network considerations

Air pollution control agencies need not undertake additional monitoring requirements in the implementation of PSI, but can simply select sites from their existing network. The sites selected, however, should generally meet two basic criteria: (1) Sites should be representative of population exposure—that is, not unduly influenced by a single emission point or background-oriented, and (2) sites should be located in areas of maximum concentration for the pollutant of interest, but should not be unduly influenced by any single source. Areas suitable for monitoring, by pollutant are:

TSP—populated areas substantially downwind of large sources or in the midst of numerous area sources.

SO<sub>2</sub>—populated areas substantially downwind of large sources or in the midst of numerous area sources.

CO—densely populated, high-traffic volume areas, including areas in the center city.

O<sub>3</sub>—populated areas substantially downwind of areas of maximum hydrocarbon emissions density, such as the central business district. The site should be 100 meters or more removed from major traffic arteries or parking lots.

NO<sub>x</sub>—populated areas downwind of areas of high traffic density.

If a pollutant(s) is (are) measured at several locations within a metropolitan area, it would be desirable (if possible) to base the index on the site showing the highest reading on a given day. This would mean that different sites would be used on different days.

For large metropolitan areas comprised of many smaller cities and suburbs where significant air quality differences may exist, the air pollution control agency may wish to report separate index values for each community. This has the additional advantages of showing the public how air pollution varies over the larger metropolitan area. Furthermore, for example, the photochemical pollutants tend to be higher in the suburban fringe.

### 5.3 Measurement practices and reporting frequencies

**5.3.1 Use of Federal reference methods.** Since PSI is based on the NAAQS, the Federal Reference Methods (FRM) or equivalent should be used where possible. Such methods are consistent with the averaging time of the primary standards. Further, continuous methods should be used, where possible, to facilitate the reporting of the index numbers two or three times per day.

**5.3.2 Carbon monoxide, nitrogen dioxide, and ozone.** The FRM for CO is based on the nondispersive infrared

measurement principle. The proposed method for NO<sub>x</sub> and the existing method for O<sub>3</sub> employ the chemiluminescence measurement principle and give continuous data. A FRM or equivalent method for CO, NO<sub>x</sub>, and O<sub>3</sub> must also meet performance specifications set forth in the *Federal Register*.<sup>10</sup>

**5.3.3 Sulfur dioxide.** The FRM for SO<sub>2</sub> is the pararosaniline 24-hour bubbler method. The solution may be analyzed automatically or manually at the central laboratory. Serious logistics problems can arise if an index number must be calculated from multiple sites two or three times per day. Fortunately, there are procedures for designating continuous SO<sub>2</sub> analyzers as equivalent to the FRM,<sup>11</sup> and from these 24-hour running averages are easily obtained. Therefore, the use of the continuous SO<sub>2</sub> analyzer is recommended to collect the data used in the index. If one is not available, then a pararosaniline 24-hour bubbler method can be used if several precautions are taken. To prevent deterioration in the sample, the sample should be collected at ambient temperature or no warmer than 15° C if ambient temperatures are below freezing. The sample should then be analyzed as soon as possible, with no later than a six-hour delay from end of sampling to analysis.

**5.3.4 Total suspended particulate.** The FRM for TSP uses a high-volume sampler and specifies a midnight-to-midnight 24-hour sample followed by a 24-hour equilibration at a relative humidity less than 50 percent. This leads to a two-day delay in the reported value. For index reporting, the simplest modification to the FRM is to make the sampling time more convenient—that is, 8 a.m.-to-8 a.m. or noon-to-noon, etc. The sample could be weighed immediately to provide a TSP value for the index. Later a true value could be calculated after the recommended equilibration time of 24 hours. A study in EPA Region IV has shown that the true TSP values are usually within 10 percent of the values measured immediately after collection.<sup>12</sup> The true value would be recorded as the correct one, reported to the National Aerometric Data Bank, and used to calculate annual averages and maxima.

**5.3.4.1 Staggered high-volume sampler measurements.** During episode conditions, the air pollution control agency may find it necessary to inform the public of existing conditions two or three times per day. Therefore, several high-volume samplers could run for 24 hour periods staggered every 4 to 6 hours throughout the episode. The sample could be weighed immediately, and that weight used in deciding what action should be taken concerning the possible emergency. Then the filter would be equilibrated for 24 hours and reweighed.

**5.3.4.2 Alternative measurements.** The paper tape sampler and the integrating nephelometer can be used to indicate the need for overlapping high-volume sampler measurements. The paper tape sampler has been used in most previous indices and has both Federal Episode

Criteria and a Significant Harm Level. The Coefficient of Haze (COH) value from the paper tape sampler, however, is poorly correlated with TSP levels. In addition, the paper tape sampler has not been determined to be an "equivalent method" to the FRM. Therefore, its use should be limited to index reporting and must not be used to determine compliance with the NAAQS for particulate matter.

A newer instrument relatively untested in routine field applications is the integrating nephelometer. It measures the scattering of light from small particles and correlates well with visibility and TSP measurements. Both the paper tape sampler and the nephelometer can produce a running 24-hour value which can be used as a qualitative indicator of TSP loadings in the atmosphere.

**5.3.5 Frequency of Reporting and Appropriate Averaging Times.** The frequency of reporting is left up to the agency, within these suggested ranges. It may be desirable to report the index once a day but probably not more than three times per day. Because the high-volume sampler has a 24-hour averaging period, agencies might consider operating two or more high-volume samplers at the same station but with off-set time periods, ending between 8 a.m. and 6 p.m. to provide reporting information during the most desirable period.

If the agency desires, the paper tape sampler or integrating nephelometer could be used in conjunction with the high-volume sampler to provide estimates of the most recent ambient particulate loading. Thus used, the paper tape sampler provides some guidance on whether or not to undertake more intensive measurements during high air pollution levels.

Appropriate averaging times for which the index should be tabulated and reported for each pollutant are:

**TSP—**TSP values taken with the high-volume sampler are discrete 24-hour values. Monitoring the data collection should be on a schedule consistent with the agency's need to report the air quality index. Other overlapping times may be employed by those agencies wishing to report more than one index value per day.

**SO<sub>2</sub>—**The suggested reporting value is the most current 24-hour running average since the last reporting period.

**CO—**Although there are two standards for CO (8 hours and 1 hour), the 8-hour standard is usually considered the limiting one and will be the one violated in the vast majority of cases. The most current 8-hour running average since the last reporting should be used. In addition, the agency could also report the index value associated with the highest 8-hour average during the reporting period.

**O<sub>3</sub>—**The suggested reporting value for O<sub>3</sub> is the highest hourly value since the last reporting period. The reporting periods are usually 24 hours or shorter.

**NO<sub>x</sub>—**Although the standard for NO<sub>x</sub> is an annual one, there are hourly values

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associated with episode criteria; therefore, using the highest hourly value since the last reporting period is recommended.

## 6. REFERENCES

1. Thom, Gary, and Wayne R. Ott. Compendium Analysis, and Review of United States and Canadian Air Pollution Indices, joint study by the U.S. Environmental Protection Agency and the Council on Environmental Quality, December 1975.
2. FEDERAL REGISTER, Vol. 36, April 30, 1971, pp. 8186-8201.
3. FEDERAL REGISTER, Vol. 36, November 25, 1971, pp. 22390-22414.
4. FEDERAL REGISTER, Vol. 36, December 17, 1971, p. 24002.
5. FEDERAL REGISTER, Vol. 36, March 18, 1974, p. 9672.
6. FEDERAL REGISTER, Vol. 40, August 20, 1975, pp. 36330-36339.
7. Ott, Wayne R. and William F. Hunt, Jr. "A Quantitative Evaluation of the Daily Air Pollution Index Proposed by the U.S. Environmental Protection Agency." Presented at the 69th Annual Meeting of the Air Pollution Control Association, Portland, Oregon, June 1976.
8. Hunt, William F., Jr., and Wayne R. Ott. Pollutant Standards Index (PSI) Evaluation Study, Joint Office of Air and Waste Management and Research and Development Report, U.S. Environmental Protection Agency, April 1976.
9. Hunt, William F., Jr., William M. Cox, Wayne R. Ott, and Gary Thom. A Common Air Quality Reporting Format, Precursor to an Air Quality Index, presented at the Fifth Annual Environment Engineering and Sciences Conference, Louisville, Kentucky, March 3-4, 1975.
10. Air Quality Criteria for Particulate Matter, USDHEW, PHS, CPEHS, NAPCA, Washington, D.C., January 1969, No. AP-49.
11. Air Quality Criteria for Sulfur Oxides, USDHEW, PHS, CPEHS, NAPCA, Washington, D.C., January 1968, No. AP-50.
12. Air Quality Criteria for Carbon Monoxide, USDHEW, PHS, CPEHS, Washington, D.C., March 1970, No. AP-62.
13. Air Quality Criteria for Photochemical Oxidants, USDHEW, PHS, CPEHS, Washington, D.C., March 1970, No. AP-63.
14. Air Quality Criteria for Nitrogen Dioxide, EPA, APCO, Washington, D.C., January 1971, No. AP-84.
15. Thom, G. C. and W. R. Ott. Atmospheric Environment, 10, 261 (1976).
16. Thom, G. C., W. R. Ott, W. F. Hunt, and J. B. Moran. "A Recommended Standard Air Pollution Index," presented at 171st National Meeting of the American Chemical Society, New York, N.Y., April 1976.
17. Knelson, John H., U.S. Environmental Protection Agency, memorandum to Raymond Smith, U.S. Environmental Protection Agency, December 15, 1975.
18. National Weather Service, Operations Manual, Air Pollution Weather Forecasts, WSOM Issuance 75-13, Part C, Chapter 30, April 1975.
19. National Weather Service, Technical Procedures Bulletin No. 122: Air Stagnation Guidance for Facsimile and Teletype (3rd Edition), October 21, 1974. (Supersedes previous TPB's Nos. 52, 58, and 69).
20. FEDERAL REGISTER, Vol. 40, February 18, 1975, pp. 7049-7070.
21. Helms, G. F. U.S. Environmental Protection Agency, Region IV, Atlanta, Georgia. Personal communication, December 1975.

APPENDIX A  
INFORMATION NEEDS FOR FORECASTING PSI

## Introduction

The information needed to qualitatively forecast the Pollutant Standards Index (PSI) is of two types: (1) pollutant-related and (2) meteorological. The pollutant-related information may include data on source locations, physical source characteristics and emissions, atmospheric-physicochemical transformation processes, and actual air quality measurements and trends. Meteorological information that may be included are data on synoptic weather features, on meteorological parameters indicative of the dispersive capability of the lower atmosphere, and of the photochemical potential. It might also include information on the effect of local terrain complexities upon meteorological parameters. Together, pollutant-related and meteorological information form the input to locally tailored predictive techniques such as mathematical models, statistically derived methods, or other techniques that may be applied along with subjective judgment to some degree.

The necessary pollutant-related information is to be obtained by the air pollution control (APC) agency having local responsibility for issuing the Index. The National Weather Service (NWS) is the primary agency supplying the needs of APC agencies for meteorological information. NWS services include issuance of advisories on air pollution potential and air stagnations. However, some APC agencies and/or their consultants may also collect and interpret meteorological information to supplement that available from the NWS.

## General data needs

The types and amounts of pollutant-related information needed will vary depending on the particular pollutant(s) of concern and the source to monitoring site configurations in the particular geographical area. For example, in the Los Angeles Basin, photochemical oxidant is the primary pollutant of concern and since precursor sources (mainly mobile) are widespread, the potential for maximum impact exists over a rather large area. In contrast, in Pittsburgh and Birmingham where suspended particulate matter from industrial ferrous emissions will most likely cause elevated pollutant levels, the maximum impact will probably be more localized; thus, pollutant-related information may not have to be as extensive. It is also important to know the diurnal, weekly, and seasonal characteristics of emissions. For instance, carbon monoxide concentrations are closely associated both spatially and temporally with automobile emissions. Typical diurnal patterns reflect morning and evening peaks in vehicular traffic. High concentrations may shift weekly in response to changes in workday versus weekend automotive travel patterns. Seasonal patterns may shift in some areas with vacation travel.

Generally, an up-to-date emissions inventory should be available for communities where PSI is to be utilized in order to adequately assess the source to monitoring site impact relationships. For point sources (usually > 100 tons/year of a pollutant), information should include the source location, pollutants emitted, emission rates, and stack parameters. Area source data, including lesser point emissions, are not normally as specific. Available area emissions, in tons per year, are usually quantified by city or county. Vehicular emissions may be estimated by combining local traffic pattern information

with documented vehicle-fleet emissions rates. These emissions data are available from the EPA National Emissions Data System (NEDS), state planning agencies, and private sources. It may be necessary to supplement these data with emissions information affecting the various temporal cycles; for instance, information on the normal operating schedules of large point sources and on traffic volume cycles in congested areas.

Trends in the concentrations of pollutants can also be useful in predicting the PSI. Trend information might include the day-to-day variation in peak hourly values or 24-hour averages. Trends data should always be evaluated relative to changes taking place or anticipated in emissions or meteorology. Persistence of a trend would especially aid in arriving at the PSI forecast if no definitive changes in emissions or meteorological features are indicated. Interpretations of trends information, on a day-to-day basis, require care and experience because of the fluctuations that for varied reasons tend to occur about a mean trend.

The types of meteorological information that could be used for forecasting the PSI have been rather well defined through past experience with forecasting methods developed in support of air pollution control activities. This support has largely dealt with forecasting indices and episodic conditions. The meteorological features and parameters that are most often utilized in forecasting air quality indices at the present time are:

Character and movement of air masses and fronts  
Areas of air mass subsidence  
Incidence, intensity, and height of inversions  
Mixing layer height  
Prevailing wind direction  
Mean wind speed (surface and mixing layer)  
Ventilation (mixing layer mean wind speed × mixing height)  
Precipitation  
Temperature  
Total sky cover

Of course, the emphasis placed on particular features and parameters listed above will vary with location and pollutant(s) of concern.

## NWS information and support services

The NWS operates a comprehensive Air Pollution Weather Forecast Program. The program is administered from NWS National and Regional Headquarters with operational program elements at the National Meteorological Center (NMC) and local Weather Service Forecast Offices (WSFO's). Details of the program are contained in the NWS Operations Manual<sup>1</sup> and Technical Procedures Bulletins.<sup>2</sup> This program generates a variety of national, regional, and local air pollution weather forecast products which are issued to the public, to control agencies, or to both, as appropriate.

The NMC is responsible for providing the large-scale meteorological guidance used by field offices in the preparation of advisories and other products which are particularized and tailored to specific geographic areas to user requirements.

The air pollution weather products of NMC are comprised of the following elements:

a. *Forecast air stagnation charts.* Issued every morning on facsimile, these four panel computer based charts depict expected areas of atmospheric stagnation (Figure 1).

b. *Air stagnation narrative.* This plain language teletype message describing the Air Stagnation Charts, is issued every morning.

<sup>1</sup>See footnotes at end of appendix.

## NOTICES

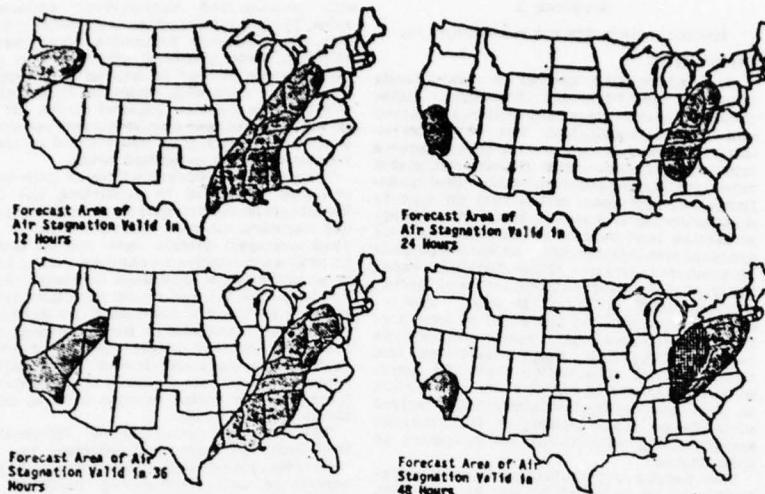


Figure 1. Sample of Stagnation Chart sent on facsimile, depicting significant areas of large-scale stagnation. Shaded area indicates area of large-scale stagnation, hatched area indicates area that is under large-scale stagnation on all four panels.

c. Air stagnation data. This computer derived teletype message currently consists of today's mixing height and transport wind speeds for selected NWS stations.

The WSPO's have responsibility for local forecast products within designated geographic boundaries, including the issuance of the following three basic air pollution products:

a. Air stagnation advisories (ASA). Issued to the public and control agencies when locally established critical values of transport wind, mixing height, and ventilation are forecast to be reached and conditions are expected to persist for at least 36 hours, causing probable significant decrease in air quality.

b. Special dispersion statements. A special product issued only to control agencies when a potential air pollution situation is determined by an NWS forecaster to exist but no ASA will be issued because such an issuance would not be in the public interest.

c. Dispersion outlooks. A routine product issued by all WSPO's where it has been deter-

mined that the APC needs routine meteorological information to facilitate day-to-day operations and adequate manpower is available at the WSPO. The format, content, and issuance times of this product is determined by the WSPO and APC. The Dispersion Outlook is issued only to the APC.

Occasionally, air pollution episodes of public concern may occur during non-stagnant situations. These involve predesignated episode levels that require control actions to improve the air quality condition. In these situations, the WSCO provides the appropriate government agencies with the meteorological support necessary for pollution control or abatement procedures.

In conjunction with these services, the NWS provides supplemental, low-level upper air soundings at designated stations. This program which provides for greater spatial and temporal detail on dispersion conditions, especially during episodes or potential episodes, is available for several cities. These locations are listed below, together with the sounding scheduled:

Location:	Program
Birmingham, Ala.	1/day routine week day, weekend and 2d daily observation call.
Charleston, W. Va.	1/day routine week day, weekend and 2d daily observation call.
Chicago, Ill.	1/day routine week day, weekend and 2d daily observation call.
El Monte, Calif.	2/day routine week days except occasionally omit afternoon soundings on well ventilated days.
Houston, Tex.	1/day routine week day, weekends and 2d daily sounding on call.
Los Angeles, Calif.	2/day, 7 days a week.
Philadelphia, Pa.	All observations on call.

Additionally, special low-level soundings are available on an on-call basis at the regular upper air observation facilities near Denver, Colo., New York, N.Y., Oakland, Calif., Pittsburgh, Pa., and Washington, D.C. An aircraft sounding is available at Sacramento, Calif. Through a cooperative effort, state APC agencies take soundings as needed in Seattle, Boston, Portland, Oreg., and San Jose, Ga. These are taken at special facilities that were established by the NWS.

The NWS has, up until recently, not been too closely involved nationwide in predicting conditions conducive to buildup of photochemical pollutants. Because of recent interest and increasing demand for such information, the NWS is in the process of evaluating possible techniques with the objective of modifying or adding to current air pollution weather forecast products and services.

## III 1

*Development of prediction methodology*

The available services and information briefly described above form the basis for developing a local community procedure for making local qualitative forecasts of the PSI. These forecasts can be reasonably made for periods up to a day in advance in terms of No Significant Change, Increase, or Decrease. It is advisable for agencies planning to use the index along with a forecast procedure to have personnel on their staffs familiar with meteorological data and how these data may be applied in development of index prediction methodology.

Considering the wealth of information available from the NWS, it seems logical that the issuance of an index forecast should be scheduled at intervals complementary to operations at the NWS. This would allow the APC agency to have the advantage of the most current NMC weather products and WSPO air pollution forecast services. In addition, it would encourage further cooperation and support of the local NWS facility. However, while it can be expected that NWS meteorologists will be able to closely coordinate with a local agency in arriving at index change predictions during potential or actual episodic conditions, they will most likely not be able to give such attention to routine day-to-day forecasting of the index. Also, NWS personnel would not be expected to have detailed knowledge of pollutant-related factors.

Where an APC agency may have developed the expertise necessary to make quantitative predictions of the PSI for the following day, they should be encouraged to make these predictions. However, it should be cautioned that making quantitative predictions of air quality or air quality indices should not be attempted without a reasonable expectation of success based on well-tested techniques. Otherwise, a less than satisfactory forecast record could result, which would tend to have an adverse effect on public acceptance of the PSI.

Mathematical air quality simulation models have to date not been used to any appreciable extent in index prediction. Because of their relative complexity, cost of modifying for local use, and time and expense that may be involved in making day-to-day predictions, their use for predicting the index qualitatively will initially be limited. However, where APC agencies may progress to the point of making quantitative forecasts, the use of models may become necessary. A listing and brief description of possible air quality models that could be applied are contained on OAQPS Guideline No. 1.2031.

*Current use of meteorological information in index prediction*

Approximately half of the 25 local agencies currently issuing air pollution indices make forecasts of their index a day in advance. Of these, only one third have meteorologists on their staffs, while the remainder rely upon NWS meteorologists for interpretation of meteorological data. Three of the local agencies were selected to serve as examples of how varying degrees of meteorological information can be incorporated into air quality index forecasting.

One of the more sophisticated forecast techniques, the Air Pollution Dispersal Index, was developed six years ago by the State of Colorado Department of Health in Denver.<sup>4</sup> A forecast is issued each morning for four time periods, a.m. today, p.m. today, a.m. tomorrow, and p.m. tomorrow. The technique developed by department meteorologists is based upon concepts of mixing heights and wind speed discussed by Holzworth in AP-101,<sup>5</sup> and employs a nomogram of wind speed vs. mixing heights, with isolines of

## NOTICES

constant ventilation factor values serving to demarcate four dispersion categories. These categories are:

Ventilation factor ( $m^3/sec.$ ) (wind speed $\times$ mixing height)	Associated dispersion
<2,000	Bad.
>2,000 to 4,000	Pain.
>4,000 to 6,000	Good.
>6,000	Excellent.

The mixing heights used for the "today" forecast are determined from a plot of the Denver morning upper air sounding, the morning minimum surface temperature at Stapleton Airport plus 2° to 4° C, and the forecast afternoon maximum temperature. The "tomorrow" mixing heights are determined from the forecast 24-hour minimum and 36-hour maximum temperature, and a forecast of the sounding using locally-tailored analytical techniques. All transport wind speeds are derived from either observed or forecast NWS data. Critical factors in Denver are the typical low-level morning inversions which serve to deteriorate air quality and the occurrence or forecast of rain or snow which automatically leads to a forecast of improving air quality.

The City of Philadelphia Department of Public Health<sup>3</sup> uses general meteorological conditions and a NWS Air Stagnation Index to predict the Philadelphia Air Quality Index. The local agency receives meteorological information twice daily from the Philadelphia NWS office. Parameters of most concern are wind speed, gustiness and the likelihood of a frontal passage with its associated turbulent mixing. Wind direction is not a vital concern since emission sources in the city are relatively well distributed in all directions. Specifically, the Air Stagnation Index is formulated from the algebraic sum of several weighted meteorological parameters as shown in Table 1. To determine the index value, the weights associated with each observed parameter are summed. When at least one of the meteorological values is associated with a "Stop," excellent dispersion is forecast. Otherwise, dispersion is forecast according to the following scheme:

Sum of weights:	Forecast dispersion
=1, -2, -3	Good.
0	M marginally good.
+1	M marginally poor.
+2, +3	Poor.

TABLE 1. Air Stagnation Check Sheet<sup>1</sup>

Meteorological parameters	Value categories	Weights
morning wind speed (knots)	> 10 < 10 > 8 < 8 > 4 < 4 = 4	-STOP -1 +1 +2
afternoon and evening wind speed (knots)	> 11 < 11 > 9 < 9 > 4 < 4 = 4	-STOP -1 +1 +2
morning mixing height (metres)	> 1500 < 1500 > 750 = 750 > 500	-STOP -1 0
afternoon ventilation factor (metres/sec.)	> 8000 < 8000 > 5000 = 5000 > 4000 = 4000	-STOP -2 0 +1

<sup>1</sup>Philadelphia Forecast Office  
National Weather Service  
National Oceanic and Atmospheric Administration  
U.S. Department of Commerce

However, due to the nature of the Philadelphia Air Quality Index, a dramatic change in dispersion is required to effect a change in the index values.

The Department of Public Health in Dallas uses meteorological data in a very qualitative manner. The general weather situation is examined daily with primary importance directed toward stagnating high pressure systems, cold frontal passages, and prevailing wind direction. NMC trajectory analysis data, surface weather patterns, and prognostic charts are used in a non-rigorous manner. For example, geographical plots of smoke and haze reports are occasionally used to determine the area extent and approach of pollutants due to large scale circulation patterns.

Improving conditions are forecast with the occurrence of precipitation, a frontal passage, and increasing wind speed. Deteriorating air quality is predicted when trajectories persist from local or more distant sources or sources areas.

Dated: August 27, 1976.

ROGER STREETLOW,  
Assistant Administrator  
for Air and Waste Management

## REFERENCES

- 1..National Weather Service, Operations Manual, Air Pollution Weather Forecasts, WSOM Issuance 75-13, Part C, Chapter 30, April 1975.
2. National Weather Service, Technical Procedures Bulletin No. 122: Air Stagnation Guidance for Facsimile and Teletype (3rd Edition), October 21, 1974. (Supersedes previous TPE's Nos. 52, 58, and 69.)
3. U.S. Environmental Protection Agency, Guidelines for Air Quality Maintenance Planning and Analysis, Volume 12: Applying Air Quality Models to Air Quality Maintenance Areas, EPA-450/4-74-012, September 1974 1974 (OAQPS No. 1.2-031), Research Triangle Park, N.C.
4. Thom, G. and Wayne R. Ott, "Compendium Analysis, and Review of United States and Canadian Air Pollution Indices," Joint Study by the U.S. Environmental Protection Agency and the Council on Environmental Quality, Washington, D.C., December 1975.
5. Holzworth, G. C. "Mixing Heights, Wind Speeds, and Potential for Urban Air Pollution Throughout the Contiguous United States," U.S. Environmental Protection Agency, Research Triangle Park, N.C. January 1972 (AP-101).

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IV a

APPENDIX IV

CONTROL OF AIR POLLUTION  
FROM AIRCRAFT AND AIRCRAFT ENGINES  
(40 CFR 87)

**Title 40—Protection of Environment**

**§ 87.1 Chapter I—Environmental Protection Agency**

**Part 87**

<b>Subpart B—Engine Fuel Venting Emissions (New and In-Use Aircraft Gas Turbine Engines)</b>	
Sec.	Sampling and analytical system for measuring exhaust emissions.
87.10	Applicability.
87.11	Standards for fuel venting emissions.
<b>Subpart C—Exhaust Emissions (New Aircraft Gas Turbine Engines)</b>	
87.20	Applicability.
87.21	Standards for exhaust emissions.
<b>Subpart D—Exhaust Emissions (In-Use Aircraft Gas Turbine Engines)</b>	
87.40	Applicability.
87.41	Standards for exhaust emissions (new aircraft piston engines).
87.42	Standards for exhaust emissions (in-use aircraft piston engines).
<b>Subpart F—Exhaust Emissions (New and In-Use Aircraft)</b>	
87.50	Applicability.
87.51	Standards for exhaust emissions (new aircraft).
87.52	Standards for exhaust emissions (in-use aircraft).
<b>Subpart G—Test Procedures for Engine Exhaust Gaseous Emissions (Aircraft and Aircraft Gas Turbine Engines)</b>	
87.60	Introduction.
87.61	Turbine fuel specifications.
87.62	Test procedure (propulsion engines).
87.63	Test procedure (auxiliary power units).
87.64	Sampling and analytical system for measuring exhaust emissions.
87.65	Information to be recorded.
87.66	Calibration and instrument checks.
87.67	Sampling procedures.
87.68	Test run.
87.69	Chart reading.
87.70	Calculations.
87.71	Compliance with emission standards.
<b>Subpart H—Test Procedures for Engine Smoke Emissions (Aircraft Gas Turbine Engines)</b>	
87.80	Introduction.
87.81	Fuel specifications.
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87.83	Information to be recorded.
87.84	Calibration and instrument checks.
87.85	Test procedures.
87.86	Test run.
87.87	Determination of SN.
87.88	Calculations.
<b>Subpart I—Test Procedures for Engine Exhaust Gaseous Emissions (Aircraft Piston Engines)</b>	
87.90	Introduction.
87.91	Gasoline fuel specifications.
87.92	Test procedure.

**PART 87—CONTROL OF AIR POLLUTION FROM AIRCRAFT AND AIRCRAFT ENGINES**

**Subpart A—General Provisions**

**Sec.**

**87.1 Definitions.**

**87.2 Abbreviations.**

**87.3 General requirements.**

**87.4 Test conditions.**

**87.5 Special test procedures.**

**87.6 Aircraft safety.**

certified on or after the effective date of the applicable emission standard.	
(10) "Rated power" means the maximum power/thrust available for takeoff at standard day conditions as approved for the engine by the Federal Aviation Administration.	
(11) "Standard day conditions" means standard ambient conditions as described in the United States Standard Atmosphere, 1962 (i.e., temperature = 59° F, relative humidity = 0%, and pressure = 29.92 inches Hg).	
(12) "Power setting" means the power output of an engine in terms of pounds thrust for turbojet and turbofan engines and shaft horsepower for turboprop and piston engines.	
(13) "Pound-thrust/hr." means pounds of thrust for 1 hour.	
(14) "Shaft horsepower" means only the measured shaft power output of an auxiliary power unit, turboprop, or piston engine.	
(15) "Auxiliary power unit" means any engine installed in or on an aircraft exclusive of the propulsion engines.	
(16) "Class TI" means all aircraft turboprop or turbojet engines except engines of Class T5 of rated power less than 8,000 pounds thrust.	
(17) "Class T2" means all turboprop or turboprop aircraft engines except engines of Class T3, T4, and T5 of rated power of 8,000 pounds thrust or greater.	
(18) "Class T3" means all aircraft gas turbine engines of the JT3D model family.	
(19) "Class T4" means all aircraft gas turbine engines of the JT8D model family.	
(20) "Class T5" means all aircraft gas turbine engines employed for propulsion of aircraft designed to operate at supersonic flight speeds.	
(21) "Class P1" means all aircraft piston engines, except radial engines.	
(22) "Class P2" means all aircraft turboprop engines.	
(23) "Taxi/Idle (in)" means those aircraft operations involving taxi and idle between the time of landing roll-out and final shutdown of all propulsion engines.	
(24) "Taxi/Idle (out)" means those aircraft operations involving taxi and idle between the time of initial starting of the propulsion engine(s) used for the taxi and turn onto duty runway.	
(25) "Exhaust emissions" means substances emitted to the atmosphere from the exhaust discharge nozzle of an aircraft or aircraft engine.	

## Title 40—Protection of Environment

§ 87.2

(28) "Fuel venting emissions" means all raw fuel, exclusive of hydrocarbons in the exhaust emissions, discharged from aircraft gas turbine engines during all normal ground and flight operations.

(27) "Smoke" means the matter in exhaust emissions which obscures the transmission of light.

(28) "Smoke number (SN)" means the dimensionless term quantifying smoke emissions.

(29) "Oxides of nitrogen" means the sum of the amounts of the nitric oxide and nitrogen dioxide contained in a gas sample as if the nitric oxide were in the form of nitrogen dioxide.

(30) "Calibration gas" means a gas of known concentration which is used to establish the response curve of an analyzer.

(31) "Span gas" means a gas of known concentration which is used routinely to set the output level of an analyzer.

§ 87.2 Abbreviations.

The abbreviations used in this part have the following meanings in both upper and lower case:

abs. Absolute.

APU Auxiliary power unit.

American Standards Association.

ASTM American Society for Testing and Materials.

b.p. Brake horsepower.

c.f.d. Cubic feet per hour.

c.i.m. Cubic feet per minute.

Centigrade.

cc. Cubic centimeter.

CO<sub>2</sub> Carbon dioxide.

CO Carbon monoxide.

EPR Engine pressure ratio.

Fahrbreit.

Federal Aviation Administration.

Department of Transportation.

Flame ionization detector.

H<sub>2</sub>/C Hydrogen to carbon atomic ratio.

HG Hydrocarbon (s).

Hg Mercury.

hp. Horsepower.

hp-hr. Horsepower-hour.

hr. Hour(s).

in. Inches of mercury.

in.Hg Vacuum.

l.D. Inside diameter.

lb. Pound(s).

LTO Landing takeoff.

min. Minute(s).

mm. Millimeter(s).

Mr. First-stage rotor speed.

Nm Second-stage rotor speed, or nitrogen (as applicable).

No Third-stage rotor speed.

N<sub>2</sub>O Nitric oxide.

NO<sub>x</sub> Oxides of nitrogen, NO' and NO<sub>2</sub>.

NO<sub>2</sub> Nitrogen dioxide.

ODER Ondispersive infrared analyzer.

O<sub>2</sub> Oxygen.

## Chapter I—Environmental Protection Agency

§ 87.21

### Subpart C—Exhaust Emissions (New Aircraft Gas Turbine Engines)

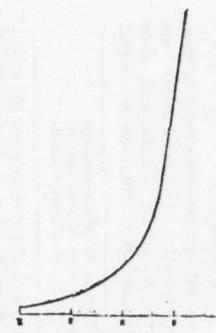
#### § 87.20 Applicability.

The provisions of this subpart are applicable to all aircraft gas turbine engines of the classes specified beginning on the dates specified.

#### § 87.21 Standards for exhaust emissions.

(a) Exhaust emissions of smoke from each new aircraft gas turbine engine of class T4 manufactured on or after January 1, 1974, shall not exceed: Smoke number of 30.

(b) Exhaust emissions of smoke from each new aircraft gas turbine engine of class T2 and of rated power of 29,000 pounds thrust or greater, manufactured on or after January 1, 1976 shall not exceed: Applicable smoke number from Figure 1.



#### § 87.22 Application.

The provisions of this subpart are applicable to each new aircraft gas turbine engine of classes T2, T3, T4, and T5 manufactured on or after January 1, 1974, and all in-use aircraft gas turbine engines of classes T2, T3, T4, and T5 beginning January 1, 1974, and each new aircraft gas turbine engine of Classes T1 and P2 manufactured on or after January 1, 1975 and all in-use aircraft gas turbine engines of classes T1 and P2 beginning January 1, 1975.

#### § 87.23 Standard for fuel venting emissions.

(a) No fuel venting emissions shall be discharged into the atmosphere from any new or in-use gas turbine engine subject to the subpart. This paragraph is directed at the elimination of intentional discharge to the atmosphere of fuel drained from fuel nozzle manifolds after engines are shut down and does not apply to normal fuel seepage from shaft seals, joints, and fittings.

(b) Conformity with the standard set forth in paragraph (a) shall be determined by inspection of the methods designed to eliminate these emissions.

(c) Exhaust emissions from each aircraft gas turbine engine of the classes specified below manufactured on or after January 1, 1979, shall not exceed:

(1) Class T1:	1.6 pounds/1,000 pound-thrust hours/cycle
(i) Hydrocarbons -----	0.4 pounds/1,000 pound-thrust hours/cycle
(ii) Oxides of nitrogen-----	3.7 pounds/1,000 pound-thrust hours/cycle
(iv) Smoke -----	Smoke number from Figure 1.
(2) Class T2, T3, or T4:	
(i) Hydrocarbons -----	0.8 pound/1,000 pound-thrust hours/cycle
(ii) Oxides of nitrogen-----	4.3 pounds/1,000 pound-thrust hours/cycle
(iv) Smoke -----	Smoke number from Figure 1.

#### § 87.24 Special test procedures.

The Administrator may, upon written application by a manufacturer or operator of aircraft or aircraft engines, prescribe test procedures for any aircraft or aircraft engine that is not susceptible to satisfactory testing by the procedures set forth herein. Prior to taking action

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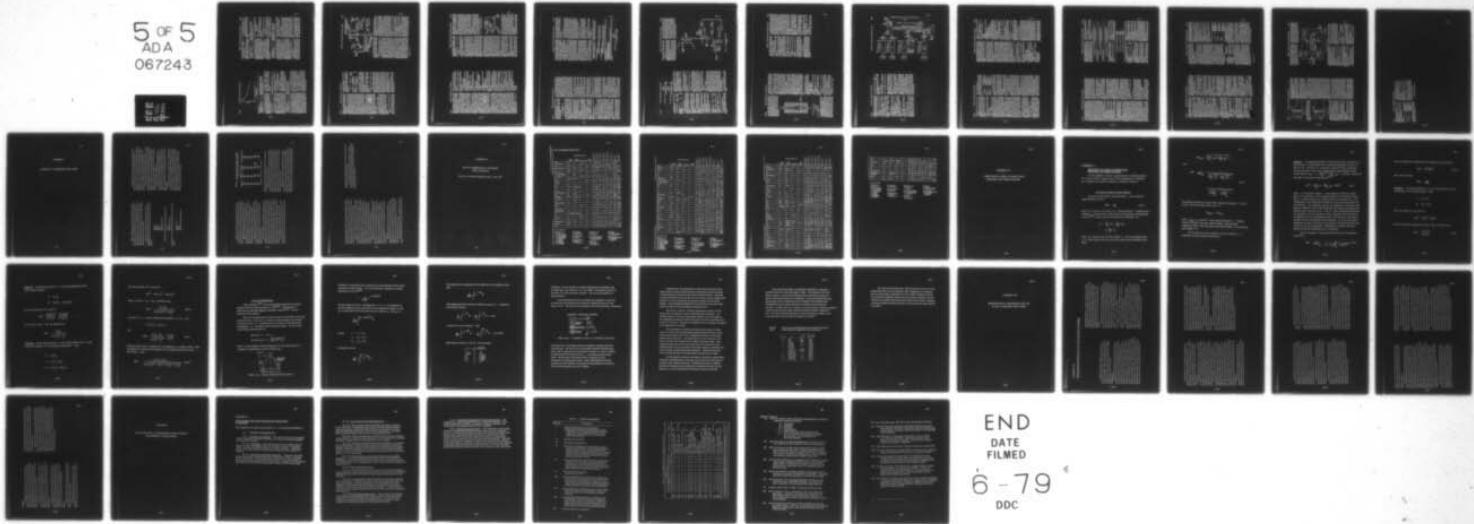
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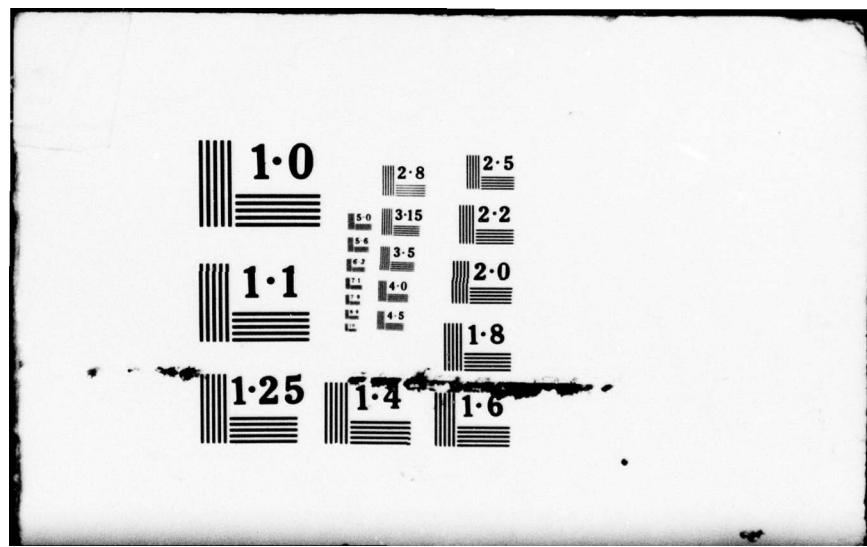
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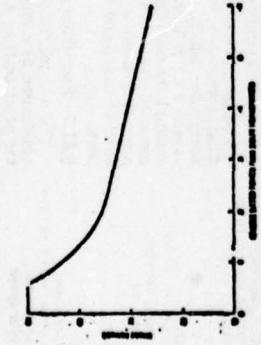
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**Title 40—Protection of Environment**

**Chapter I—Environmental Protection Agency**

**§ 87.60**



**Subpart E—Exhaust Emissions (New and In-Use Aircraft Piston Engines)**

**§ 87.40 Application.**

The provisions of this subpart are applicable to all aircraft piston engines of class P1, beginning on the date specified:

(i) Carbon monoxide ..... 8 pounds/1,000 pound-thrust hours/cycle  
 (ii) Oxides of nitrogen ..... 3 pounds/1,000 pound-thrust hours/cycle  
 (iv) Smoke ..... Smoke number from Figure 1.

**Subpart F—Exhaust Emissions (New and In-Use Aircraft)**

**§ 87.50 Applicability.**

The provisions of this subpart are applicable to all aircraft beginning on the date specified.

(a) Exhaust emissions from each new aircraft piston engine manufactured on or after December 31, 1979, shall not exceed:

8 pounds/1,000 pound-thrust hours/cycle

(b) The standards set forth to a composite gaseous exhaust emission sample representing the operating cycle set forth in the application sections of Subpart I of this part and measured and calculated in accordance with the procedures set forth in that subpart.

**§ 87.42 Standards for exhaust emissions (in-use aircraft piston engines).**

Exhaust emissions from each in-use aircraft piston engine manufactured on or after January 1, 1979, shall not exceed the level applicable to such engine when it was new.

(i) Hydrocarbons ..... 0.4 pound/1,000 hp-hr. of power output  
 (ii) Carbon monoxide ..... 8 pounds/1,000 hp-hr. of power output  
 (iii) Oxides of nitrogen ..... 3 pounds/1,000 hp-hr. of power output.

**Subpart G—Test Procedures for Engine Exhaust Gaseous Emissions (Aircraft and Aircraft Gas Turbine Engines)**

**§ 87.60 Introduction.**

Except as provided under § 87.5, the procedures described in this subpart shall be the test program to determine the conformity of new and in-use aircraft gas turbine engines with the applicable standards set forth in this part. The procedures shall also be used to determine emissions from auxiliary power units in determining conformity of new and in-use aircraft with the applicable standards set forth in this part.

(a) The test consists of operating the engine at prescribed power settings on an engine dynamometer (for engines producing primarily shaft horsepower) or thrust measuring test stand (for engines producing primarily thrust). The aircraft manufactured on or after January 1, 1979, resulting from generation of onboard power shall not exceed the level of the emission standards applicable to such aircraft when it was new.

**§ 87.52 Standards for exhaust emissions (In-use aircraft).**

Exhaust emissions from each in-use aircraft manufactured on or after January 1, 1979, resulting from generation of onboard power shall not exceed the level of the emission standards applicable to such aircraft when it was new.

**Subpart D—Exhaust Emissions (In-Use Aircraft Gas Turbine Engines)**

**§ 87.50 Application.**

The provisions of this subpart are applicable to all in-use aircraft gas turbine engines certified for operation within the United States of the classes specified beginning on the dates specified:

(i) Hydrocarbons ..... 0.6 pound/1,000 pound-thrust hours/cycle  
 (ii) Carbon monoxide ..... 26.8 pounds/1,000 horsepower-hours/cycle  
 (iii) Oxides of nitrogen ..... 12.9 pounds/1,000 horsepower-hours/cycle  
 (iv) Smoke ..... Smoke number from Figure 2.

**Subpart H—Exhaust Emissions (In-Use Turboprop Engines)**

**§ 87.50 Applicability.**

The provisions of this subpart are applicable to all in-use aircraft gas turbine engines certified for operation within the United States of the classes specified beginning on the dates specified:

(i) Hydrocarbons ..... 0.6 pound/1,000 pound-thrust power cycle  
 (ii) Carbon monoxide ..... 0.043 pound/rated power/cycle  
 (iii) Oxides of nitrogen ..... 0.0015 pound/rated power/cycle.

**Subpart I—Exhaust Emissions (In-Use Turboprop Engines)**

**§ 87.50 Applicability.**

The provisions of this subpart are applicable to all in-use aircraft gas turbine engines of class T4, beginning January 1, 1974, shall not exceed: Smoke number of 30.

(b) Exhaust emissions of smoke from each in-use aircraft gas turbine engine of class T2 and of rated power of 29,000 pounds thrust or greater, beginning January 1, 1976, shall not exceed: Aplicable Smoke number from Figure 1.

(c) Exhaust emissions of smoke from each in-use aircraft gas turbine engine of class T3, beginning January 1, 1978 shall not exceed: Smoke number of 25.

exhaust gases generated during engine operation to determine its mass emission rates and work output.

(D) The exhaust emission test is designed to measure hydrocarbons, carbon monoxide, carbon dioxide, and oxides of nitrogen concentrations and determine mass emissions and engine work output through calculations during a simulated aircraft landing-takeoff cycle (LTO).

The LTO cycle is based on time periods at data during high activity periods at major airports. The test for propulsion engines consists of at least the following five modes of engine operation: Taxi (test), takeoff, climboff, approach, and taxi (idle). The mass emission and work output for the modes are combined to yield the reported values. The test for auxiliary power units consists of one mode: Full load.

(e) When an engine is tested for exhaust emissions on an engine dynamometer or test stand, the complete engine assembly, including all accessories, which

might reasonably be expected. In some emissions to the atmosphere stalled and functioning but excluding auxiliary gearbox-mounted components required to drive aircraft systems services air bleed.

<p><b>§ 87.61</b> Turbine fuel specifications.</p> <p>For exhaust emission testing, fuel meeting the specifications: ASTM D1655-Latest version-Jet A, shall be used. Non-metallics additives as specified in ASTM D1655-Latest version-Jet A, may be present. Additives used for the purpose of smoke suppression (such as organo-metallic compounds) shall not be present.</p>	<p><b>§ 87.62</b> Turbine engines (exclusion en-</p>
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(a) (1) The engine shall be tested in each of the following five engine operating modes which simulate aircraft engines.

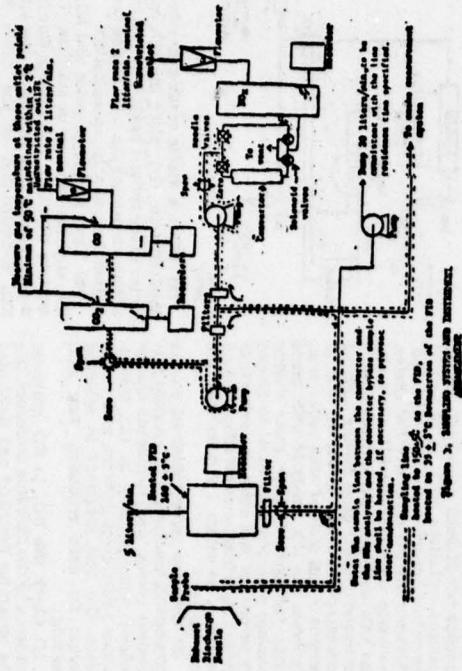
### **§ 87.63 Test procedure (auxiliary power)**

(a) In determining compliance with the aircraft emission standards under Subpart P of this part, each auxiliary power unit shall be tested at its maximum load condition as indicated by its power output, exhaust gas temperature, and other parameters as specified in data sheet 1.

or turbine inlet temperature to determine its mass emission rate and work output. The work output shall be determined as a combination of shaft energy output and actual bleed air energy component. The bleed air equivalent horsepower for AFRP's shall be determined as follows:

(b) Emission testing shall be conducted on warmed-up auxiliary power units which have achieved a steady operating temperature.

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If the effect is greater than 2 percent measured CO levels, all subsequent measurements shall be corrected for these interferences.

(c) **Component description** (exhaust gas sampling system). The following components shall be used in the exhaust sampling system:

(a) Schematic drawing. Figure 3 is a schematic drawing of the exhaust gas sampling and analytical system which shall be used for testing under the regulations given in this subpart.

all sampling holes shall be of equal diameter. Total pressure orifice area shall drop such that the principal pressure drop

(at least 80 percent) through the probe assembly shall be taken at the orifice and coordinate the functions of the computer.

point systems. Parallel installation of CO and CO<sub>2</sub> instruments are an acceptable alternate configuration of Figure 3.

(a) A minimum of 12 sampling points shall be used. Either mixing or individual measurements.

(b) Water removal devices. No desiccants, dryers, water traps, or related equipment may be used to remove water from the environment prior to analysis.

(b) A minimum of three different probes are acceptable.

(c) If the minimum of 12 sampling radial positions shall be used in each of the four quadrants.

points is used, the points in circumferentially adjacent sampling areas shall be separated by at least 80° angular displacement. No two sampling points shall be separated in any direction by a distance less than 0.1 tailpiece radius or 0.1

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**exhaust height, as applicable. If the number of sampling points (n) is greater than 12, they shall be equal in number in each quadrant or sector and the minimum separations specified above shall be reduced by a factor of 12/n.**

(d) The axial sampling plane shall be as close to the plane of the exit nozzle as engine performance parameters permit, but in any case, shall be within one exit nozzle diameter of the exit plane. In all cases, the probe shall be designed to obtain a representative sample over the area of the entire exhaust nozzle, on both mixed fan engines and nonmixed fan engines as well as turbojets, turboprops and auxiliary power engines.

(e) The multipoint probe shall be designed to minimize the errors due to plenum stratification, whether the stratification is due to combustor design, mixing or lack of mixing, or engine design such as mixing of fan and core air. (f) Sample transfer. The sample shall be transferred from the probe to the analytical instruments through a heated sample line of either stainless steel or Teflon of 0.16- to 0.32-in. I.D. The sample line shall be maintained at a temperature of 150° $\pm$ 5° C. Sample flow rates from the engine to the instruments are 5 ft<sup>3</sup>/sec. or less. The sample line length from the probe exit to the instruments shall be of minimum length, but in no case greater than 60 feet.

(g) Component description (exhaust gas analytical system). The following components shall be used in the exhaust gas analytical system for testing under the regulations in this subpart. The analytical system provides for the determination of hydrocarbon concentrations by flame ionization detector analysis, the determination of carbon monoxide and carbon dioxide concentrations by nondispersive infrared analysis and the determination of oxides of nitrogen concentrations by chemiluminescence analysis of exhaust samples. The chemiluminescence method of analysis requires that the nitrogen dioxide present in the sample be converted to nitric oxide before analysis. Other types of analyzers may be used if shown to yield equivalent results and if approved in advance by the Administrator. See Appendix A of this part.

(h) EPA note, July 17, 1973, as amended at 46 FR 26748, Dec. 14, 1979]

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(1) Pollutant concentration, from recorders, in percent or parts per million by volume, and parts per million carbon for hydrocarbons. **§ 67.66 Calibration and instrument checks.**

(a) Calibrate the analytical assembly at least once every 30 days. Use the same flow rate as when analyzing samples. (b) Adjust analyzers to optimize performance.

(c) Zero the hydrocarbon analyzer with zero grade air and the carbon monoxide, carbon dioxide, and oxides of nitrogen analyzers with zero grade nitrogen. The allowable zero gas impurity concentrations should not exceed 0.1 p.p.m. equivalent carbon response, 1 p.p.m. carbon monoxide, 250 p.p.m. carbon dioxide, and 0.1 p.p.m. nitric oxide.

(d) Set the CO and CO<sub>2</sub> analyzer gains to give the desired range. Select desired attenuation scale of the HC analyzer and adjust the electronic gain control to give the desired full scale range. Select the desired scale of the NO<sub>x</sub> analyzer and adjust the prototype high voltage supply or amplifier gain to give the desired range.

(e) Calibrate the HC analyzer with propane (air diluent) gases having nominal concentrations equal to 50 and 95 percent of full scale of each range used. Calibrate the CO analyzer with carbon monoxide (nitrogen diluent) gases and the CO<sub>2</sub> analyzer with carbon dioxide (nitrogen diluent) gases having nominal concentrations equal to 30, 60, and 90 percent of full scale of each range used. Calibrate the NO<sub>x</sub> analyzer with nitric oxide (nitrogen diluent) gases having nominal concentrations equal to 50 and 90 percent of full scale of each range used. The actual concentrations should be known to within  $\pm$  2 percent of the true values.

(f) Compare values obtained on the CO and CO<sub>2</sub> analyzers with previous calibration curves. Any significant change reflects some problem in the system. Locate and correct problem, and recalibrate. Use best judgment in selecting curves for data reduction. Log gain reading.

(g) Check the NO<sub>x</sub> to NO converter efficiency by the following procedure. Use the apparatus described and illustrated in Figure 4.

(h) Attach the NO/N<sub>2</sub> supply (150-250 p.p.m.) at C2, the O<sub>2</sub> supply at C1 and the analyzer inlet connection to the effluent line at C3. The NO concentration should be equal to or greater than

concentrations of NO are used, air may be used in place of O<sub>2</sub> to facilitate better control of the NO<sub>x</sub> generated during step (iv).

(i) With the efficiency detector bypass off, place the NO<sub>x</sub> converter in bypass mode and close valve V3. Open valve MIV2 until sufficient flow and stable readings are obtained at the analyzer. Zero and span the analyzer output to indicate the value of the NO concentration being used. Record this concentration.

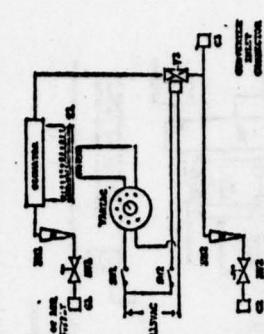
(ii) Open valve V3 (on/off flow control solenoid valve for O<sub>2</sub>) and adjust valve MIV1 (O<sub>2</sub> supply pressure valve) to blend enough O<sub>2</sub> to lower the NO concentration (iii) about 10%. Record this concentration.

(iv) Turn on the ozonator and increase its supply voltage until the NO concentration of (iii) is reduced to about 20% of (ii). NO<sub>x</sub> is now being formed from the NO+O<sub>2</sub> reaction. There must always be at least 10% unreacted NO at this point. Record this concentration.

(v) When a stable reading has been obtained from (iv), place the NO<sub>x</sub> converter in the convert mode. The analyzer will now indicate the total NO<sub>x</sub> concentration. Record this concentration.

(vi) Turn off the ozonator and allow the analyzer reading to stabilize. The mixture NO+O<sub>2</sub> is still passing through the converter. This reading is the total NO<sub>x</sub> concentration of the dilute NO<sub>x</sub> span gas used at step (iii). Record this concentration.

(vii) Close valve V3. The NO concentration should be equal to or greater than



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the reading of (iii) indicating whether the NO contains any NO<sub>x</sub>. Calculate the efficiency of the NO<sub>x</sub> converter by substituting the concentrations obtained during the test into the following equation.

$$\% \text{ Eff.} = \frac{(n) - (m)}{(n) - (l)} \times 100\%$$

The efficiency of the converter should be greater than 90 percent. Adjusting the converter temperature may be needed to maximize the efficiency. Efficiency checks should be made on each analyzer range using an NO span gas concentration appropriate to the instrument range.

(vii) If the converter efficiency is not greater than 90 percent, the cause of the inefficiency shall be determined and corrected before the instrument is used. (viii) The converter efficiency shall be checked at least once weekly and preferably once daily.

(b) Verifications and instrument checks shall be performed in accordance with § 87.67 on in-use systems. Verification and instrument checks shall be performed before and after each test, but not less than once per hour.

(c) For the purposes of this section, the term "zero grade air" includes artificial "air" consisting of a blend of nitrogen and oxygen with oxygen concentrations between 18- and 21-mole percent.

16 CFR 1600, July 17, 1973, as amended at 16 CFR 3773, Dec. 18, 1973]

**§ 87.67 Sampling procedures.**

(a) HC, CO, CO<sub>2</sub>, and NO<sub>x</sub> measurements. Allow a minimum of 2 hours warming for the CO, CO<sub>2</sub>, HC, and NO<sub>x</sub> analyzers. (Power is normally left on infrared and chemiluminescence analyzers; but when not in use, the chopper motors of the infrared analyzers are turned off and the phototube high voltage supply of the chemiluminescence analyzer is placed in the standby position.) The following sequence of operations shall be performed in conjunction with each series of measurements:

(1) Check the sampling system for any leaks that could dilute the exhaust gas and replace or clean sample line filters.

(2) Introduce the zero grade gas at the same flow rates used to analyze the test samples and zero the analyzers. Obtain a stable zero on each amplifier and recorder. Recheck after tests.

(3) Introduce span gases and set the CO and CO<sub>2</sub> analyzer gains, the HC analyzer sample capillary flow rate and electronic gain control. If provided, and the NO<sub>x</sub> analyzer high voltage supply or amplifier gain to match the calibration curves. In order to avoid corrections, span and calibrate at the same flow rates used to analyze the test samples. Span gases should have concentrations equal to approximately 80 percent of each range used. If gain has shifted significantly on the CO or CO<sub>2</sub> analyzers, check tuning. If necessary, check calibration. Respan at least at end of test, but not less than once per hour. Show actual concentrations on chart. Log gain readings.

(4) Check zeros; repeat the procedure in subparagraphs (1) and (2) of this paragraph, if required.

(5) Check sample line temperature and sample residence time. To check sample residence time:

(i) Introduce HC span gas into sampling system at sample inlet and simultaneously start timer.

(ii) When HC instrument indication is 15 percent of span concentration, stop timer.

(iii) If elapsed time is more than 2.0 seconds, make necessary adjustments.

(iv) Repeat (i) through (iii) with CO, CO<sub>2</sub>, and NO instruments and span gases.

(6) Check instrument flow rates and pressures.

(7) The engine shall be operated in each operating mode until emission levels have stabilized as indicated by a constant instrument reading or recorder output. This stabilized reading shall be recorded and used in calculating mass emission rates as called for in Section 87.70.

(8) Measure, HC, CO, CO<sub>2</sub>, and NO<sub>x</sub> concentrations of the exhaust sample at the various modes called for in § 87.62 or 87.63, as appropriate.

(9) If individual probes are used, the number to be reported (for each component) shall be the arithmetic average of the values obtained at each sampling point. If mixing probes are used, the number to be reported shall be the average of the values of the several probes, giving each probe a weighting factor equal to the number of sample points in that particular probe.

(10) Recheck zero and span points at the end of the test and also at approximately one hour intervals during the

test. If either has changed by  $\pm 2$  percent of full scale, the test shall be rerun after instrument maintenance. Provided, that if it is impractical to repeat the test, a correction based on an interpolation which is linear with time is acceptable for corrections within  $\pm 4$  percent.

**(b) Sample system contamination.**

(1) Care shall be taken to avoid loading of the sampling system with raw fuel discharge during engine starting.

(2) When the sample probe is in the exhaust stream and sampling is not in process, a back purge with air or an inert gas may be necessary to protect the probe and sample line from particulate buildup which could affect smoke and hydrocarbon readings. Check sample line for contamination each time the instrument zero and span points are checked. Use the following procedure to check the sample line:

(i) Immediately after instrument zero and span measurements and necessary adjustments are complete, introduce hydrocarbon zero gas near the sample probe. If the instrument zero reading increases by more than 5 percent of the scale in use, the sample line shall be purged or cleaned as required, to bring the zero within limits.

(ii) When the requirements of (1) have been met, introduce hydrocarbon span gas into the inlet of the sampling

**§ 87.68 Test run.**

A test run shall consist of operating the engine in accordance with § 87.62 or 87.63, as applicable. During the test run, the engine shall not be operated at a power setting above normal idle power before beginning the test sequence of § 87.62. The engine shall be operated in the sequence called for under these sections, unless an alternate procedure is agreed to in writing by the Administrator before such testing is conducted. If repeat runs at full takeoff power are necessary, they may be conducted after the last idle run in the test sequence.

**§ 87.69 Chart readings.**

Determine the HC, CO, CO<sub>2</sub>, and NO<sub>x</sub> concentrations of the exhaust sample during the various modes from the instrument deflections or recordings, making use of appropriate calibration charts.

**(a) The final reported test results shall be computed by use of the following formulas:**

(1) Hydrocarbon:

$$\text{HC pounds/1,000 pound-thrust-hrs. or } \frac{\text{Sum of the HC mass/mode of en. mode}}{1,000 \text{ hp-hr. as appropriate/cycle}}$$

(2) Carbon monoxide:

$$\text{CO pounds/1,000 pound-thrust-hrs. or } \frac{\text{Sum of the CO mass/mode of en. mode}}{1,000 \text{ hp-hr. as appropriate/cycle}}$$

(3) Oxides of nitrogen:

(a) The pollutant mass and work output per mode shall be computed by use of the following formulas:

(i)  $\text{NO}_{x} \text{ pounds/1,000 pound-thrust-hrs. or } \frac{\text{Sum of the NO}_x \text{ mass/mode of en. mode}}{1,000 \text{ hp-hr. as appropriate/cycle}}$

(ii)  $\text{CO}_{2} \text{ pounds/1,000 pound-thrust-hrs. or } \frac{\text{Sum of the CO}_2 \text{ mass/mode of en. mode}}{1,000 \text{ hp-hr. as appropriate/cycle}}$

(iii)  $\text{NO} \text{ emissions rate } \times \text{TPM}$

(iv)  $\text{CO} \text{ emissions rate } \times \text{TPM}$

(v)  $\text{NO}_x \text{ emissions rate } \times \text{TPM}$

(vi) Work output of each mode  $\times$  power (in 1000 pounds thrust of 1000 horse power)  $\times$  TPM.

(b) The emissions rates for each mode shall be computed by use of the following formulas:

(1)  $\text{HC emission rate} = \frac{(\text{HC})}{\text{Mass/Mode}}$

(2)  $\text{CO emission rate} = \frac{(\text{CO})}{\text{Mass/Mode}}$

(3)  $\text{NO}_x \text{ emission rate} = \frac{(\text{NO}_x)}{\text{Mass/Mode}}$

(4)  $\text{CO}_2 \text{ emission rate} = \frac{(\text{CO}_2)}{\text{Mass/Mode}}$

(5)  $\text{NO} \text{ emissions rate } \times \text{TPM}$

(6) Work output of each mode  $\times$  power (in 1000 pounds thrust of 1000 horse power)  $\times$  TPM.

(c) The emissions rates for each mode shall be computed by use of the following formulas:

(1)  $\text{HC emission rate} = \frac{(\text{HC})}{\text{Mass/Mode}}$

(2)  $\text{CO emission rate} = \frac{(\text{CO})}{\text{Mass/Mode}}$

(3)  $\text{NO} \text{ emissions rate } \times \text{TPM}$

(4)  $\text{CO} \text{ emissions rate } \times \text{TPM}$

(5)  $\text{NO}_x \text{ emissions rate } \times \text{TPM}$

(6) Work output of each mode  $\times$  power (in 1000 pounds thrust of 1000 horse power)  $\times$  TPM.



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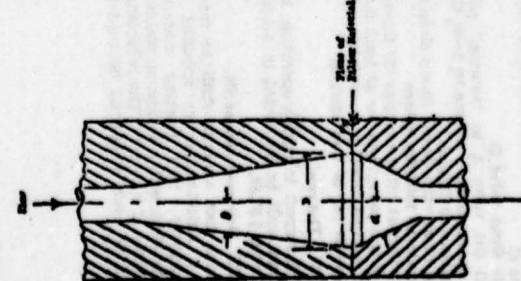
(d) **Filter holder.** The filter holder shall firmly clamp the filter material so that overall system leakage does not exceed that provided in § 87.84(c). The holder internal geometry shall be such that the variation of SN over the sample spot surface is not greater than two. Required elements of the filter holder design are given in Figure 6. The filter holder shall be made of corrosion resistant material.

(e) **Vaiving.** Four valve elements shall be provided. Valve A shall be a quick acting, "full-flow, flow diverter with "closed," "sample," and "bypass" positions. Valve A may consist of two valves, provided that they are interlocked so that one of the pair cannot act independently of the other. Valves B and C shall be throttling valves used to establish a system flow rate. Valve D shall be a shutoff valve used in isolating the filter holder. All valves shall be made of corrosion resistant material.

(f) **Vacuum pump.** The vacuum pump shall have a no-flow vacuum capability of at least 22 in. Hg. N., and full-flow capacity of 1 a.c.i.m. minimum.

(g) **Reflectometer.** A reflectometer conforming to ASA standard for diffuse reflection density, number Ph2.17-1958, shall be used. The diameter of the reflectometer light beam on the filter paper shall be no more than one-half of "D," the diameter of the filter spot. The allowable range of "D" is given in Figure 6.

(h) **Filter material.** The filter material shall be Whatman No. 4 filter paper or equivalent approved by the Administrator.



2 (Open diameter) = 1.0 ± 1.0 in  
0.5 ± 1.0 in  
0.5 ± 0.5 in  
0.5 ± 0.5 in  
Dimensions in inches unless otherwise specified

(i) **Sampling probe.** The sample probe and procedure shall be the same as used to show compliance with § 87.84(c).

(j) **Sampling lines.** The sampling lines shall be straight through with no kinks or loops, and no bends having a radius of less than 10 line diameters. Sampling lines inside diameter shall be within 0.18 to 0.32 inch. The sampling line section from the probe exit to valve A entrance shall be of minimum length, not greater than 15 feet, with a minimum of fittings

(k) **Precautions:** The material being measured is composed of low-micron and/or submicron size agglomerated particles. Precautions should be taken to assure that steady state conditions have been achieved prior to taking a sample. To prevent material accumulation, the system shall not be left in a no-flow condition when exhaust gas is contained.

(l) **Sampling:** Not less than 1 minute shall be allowed to assure that the system is fully charged with a representative gas sample. The sampling flow rate shall be maintained at  $0.50 \pm 0.02$  c.f.m. At least four sample sizes shall be taken within the range of  $0.00765$  to  $0.115$  lb. of exhaust gas per square inch of filter. Samples shall be taken both above and below  $0.025$  lb. of exhaust gas per square inch of filter.

(m) **Temperature control:** The gas temperature from the sampling probe entrance to the filter material shall be above the dew point temperature. All lines and valves shall be lagged and/or heated as necessary to meet this requirement.

(n) **Preparation for each power setting:** The following shall be done to prepare the system at each power setting:

- (1) Set valve A to "bypass," close valve D.
  - (2) Draw exhaust gas for 5 minutes.
  - (3) Clamp clean filter material into the holder.
  - (4) Close valve A, full open valves B, C, and D.
  - (5) Run the vacuum pump for 5 minutes.
- The system shall be satisfactory if no more than 0.20 standard cubic foot passed through the volume meter during 5 minutes. The system shall not be used until this requirement has been met.

#### § 87.83 Test procedure.

- (a) The engine shall be operated as provided in § 87.62. The leak check and cleanliness check requirements of § 87.84 shall be confirmed before and after each engine test. The test shall be repeated if the requirements of § 87.84 are not confirmed.

**§ 87.83 Information to be recorded.**  
The following information shall be recorded with respect to each test in accordance to that information called for in § 87.85 (a) through (c).

(a) Sample temperature.

(b) Sample pressure.  
(c) Actual sample volume at sampling conditions.

(d) Actual sample flow rate at sampling conditions.  
(e) Leak and cleanliness checks substitution as required by § 87.84 (b) and (c).

**§ 87.84 Calibration and instrument checks.**

(a) **Reflectometer calibration.** The reflectometer required by § 87.82(t) (8) shall be calibrated in accordance with manufacturer's specifications.

(b) **System maintenance.** The need for cleaning or replacement shall be determined by conducting the following cleanliness check:

- (1) Full open valves B, C, and D.

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$0.50 \pm 0.02$  c.f.m. This shall be done quickly before particulate buildup on the filter causes excessive pressure drop.

(d) Set valve A to "bypass" and close valve D.

(e) Clamp clean filter material into the holder.

(f) Sampling procedure: The procedure for smoke sampling at each power setting shall be as follows:

(1) With valve D closed and valve A set at the "bypass" position, charge the lines with exhaust gas for 1 minute minimum.

(2) Open valve D.

(3) Set valve A to "sample," allow the chosen sample volume to pass, then set valve A to "bypass."

(4) Close valve D and clamp clean filter material into the holder.

(5) Repeat subparagraphs (2) through (4) of this paragraph for at least three more sample sizes in accordance with paragraph (c) of this section.

§ 87.86 Test run.

With respect to engine operation, the test run shall be conducted in accordance with § 87.88.

#### § 87.87 Determination of SN.

Smoke spot analysis shall be made with a reflectometer as specified in § 87.82(b)(8). The backing material shall be black with a maximum absolute reflectance of 3 percent. The reflectance reading of each spot shall be used to

calculate SN by:  $SN = 100(1 - \frac{R_s}{R_w})$ , where  $R_s$  = absolute reflectance of the sample spot,  $R_w$  = absolute reflectance of clean filter material.

#### § 87.88 Calculations.

(a) Calculation of W. The sample weight (W) shall be calculated by:

$$W (\text{lb.}) = 1.328 \frac{T}{P} V^{\frac{1}{3}}$$

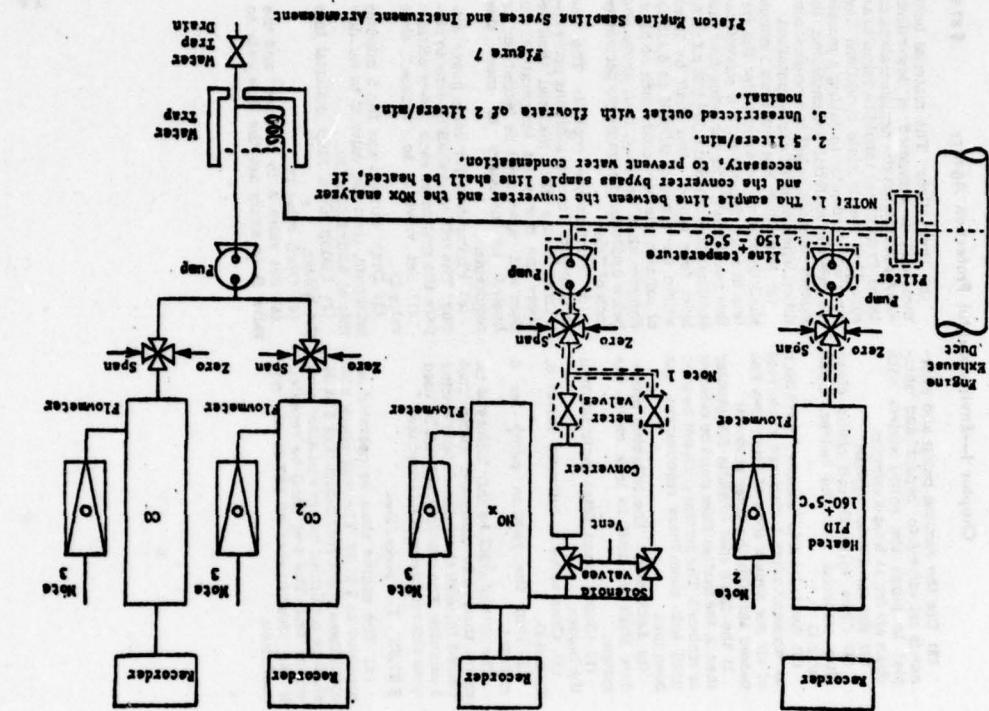
where V is measured sample volume in cubic feet, P is sample pressure and temperature in units of inches of mercury absolute and degrees Rankine, respectively, measured immediately upstream of the volume meter. V is measured sample volume in cubic feet.

(b) Calculation of W/A. The sample weight in pounds per square inch of filter spot area (W/A) shall be calculated for each sample size taken.

(c) Plotting SN versus W/A. All SN shall be plotted versus W/A on semilog coordinates, with W/A as the logarithmic abscissa. A straight line shall be fitted to these points using the method of least squares. Such a line shall be produced for each power setting specified.

(d) Plotting reporting values of SN versus power setting. Values of SN shall be read from the straight line functions of paragraph (c) of this section for  $W/A = 0.0230$  lb./sq. in. These SN are the values to be reported and shall be presented by plotting them as ordinate versus power setting as abscissa on rectangular coordinates.

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#### Compliance with emission standards.

Compliance with each emission standard shall be determined by comparing the plot of SN versus power setting from § 87.85 with the applicable emission standard under this part. The SN at every power setting shall not exceed the standard set forth in this part.

#### Subpart I—Test Procedures for Engine Exhaust Gaseous Emissions (Aircraft Piston Engines)

##### § 87.90 Introduction.

Except as provided under § 87.5, the procedures described in this subpart shall be the test program to determine the conformity of new and in-use aircraft piston engines with the applicable standards set forth in this part.

(a) The test consists of operating the engine at prescribed power settings on an engine dynamometer or test stand. The exhaust gases generated during engine operation are sampled continuously for specific component analysis through the analytical train.

(b) The exhaust emission test is designed to measure hydrocarbon, carbon monoxide, and oxides of nitrogen concentrations and determine mass emissions through calculations during a simulated aircraft landing/takeoff cycle (LTO). The LTO cycle is based on time in mode data during high activity periods at major airports. The test consists of five modes of engine operation: Taxi/taxi (out), takeoff, climbout, approach, and taxi/taxi (in). The mass emissions for the modes and engine rated power are combined to yield the reported values.

(c) When an engine is tested for exhaust emissions on an engine dynamometer or test stand, the complete engine shall be used with all accessories, which might reasonably be expected to influence emissions to the atmosphere, installed and functioning.

##### § 87.91 Gasoline feed specifications.

For exhaust emission testing, fuel meeting the specifications of ASTM D910 latest version for grades 80/87 or 100/130 (as applicable) shall be used.

The lead content and octane rating of the fuel shall be in the range recommended by the engine manufacturer.

§ 87.92 Test procedures.

(a) (1) The engine shall be tested in each of the following six engine operating modes which simulate aircraft operation to determine its mass emission rates:

##### Power setting (percent of rated power)

See subparagraph (2) of this paragraph

100 percent

See subparagraph (3) of this paragraph

40 percent

See subparagraph (4) of this paragraph

Approach

Taxi/taxi (in)

Takeoff

Climbout

Approach

Taxi/taxi (out)

Takeoff

Climbout

Approach

Taxi/taxi (in)

Takeoff

Climbout

Approach

Taxi/taxi (out)

Takeoff

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Approach

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Takeoff

Climbout

Approach

Taxi/taxi (in)

Takeoff

Climbout

Approach

(a) (1) The engine shall be tested in each of the following six engine operating modes which simulate aircraft operation to determine its mass emission rates:

(b) (1) The engine shall be tested in accordance with the recommendations of the manufacturer.

(c) (1) The engine shall be tested in accordance with the recommendations of the manufacturer.

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tain a stable zero on each amplifier meter and recorder. Recheck after tests.

(b) Introduce span gases and set the CO and CO<sub>2</sub> analyzer gains, the HC and NO<sub>x</sub> analyzer capillary flow rate and electronic gain control. If provided, and the NO<sub>x</sub> analyzer high voltage supply or amplifier gain to match the calibration curves. In order to avoid corrections, span and calibrate at the same flow rates used to analyze the test samples. Span gases should have concentrations equal to approximately 50 percent of each range used. If gain has shifted significantly on the CO or CO<sub>2</sub> analyzers, check tuning. If necessary, check calibration. Repeat at least at end of test but not less than once per hour. Show actual concentrations on chart. Log gain readings.

(c) Check zeros: repeat the procedure in subparagraphs (1) and (2) of this paragraph if required.

(d) Check sample line temperature and sample residence time. To check sample residence time:

(i) Introduce HC span gas into sampling system at sample inlet and simultaneously start timer.

(ii) When HC instrument indication is 15 percent of span concentration, stop timer.

(iii) If elapsed time is more than 2.0 seconds, make necessary adjustments.

(iv) Repeat (i) through (iii) with CO, CO<sub>2</sub>, and NO instruments and span gases.

(v) Check instrument flow rates and pressures.

(vi) The engine shall be operated in each operating mode until emission levels have stabilized as indicated by a constant instrument reading or recorder output. This stabilized reading shall be recorded and used in calculating mass emission rates as called for in § 87.99.

(vii) Measure HC, CO, CO<sub>2</sub>, and NO<sub>x</sub> concentrations of the exhaust sample at the various modes called for in § 87.92.

(viii) Recheck zero and spans points at the end of the test and also at approximately one hour intervals during the test. If either has changed by  $\pm 2$  percent of full scale, the test shall be rerun after instrument maintenance: Provided, That if it is impractical to repeat the test, a correction based on interpolation linear with time is acceptable for corrections within  $\pm 4$  percent.

(ix) Carbon balance. As a test of representative sample collection, a carbon balance shall be calculated from air and fuel flow data. This balance shall be

within  $\pm 5$  percent of that calculated from exhaust gas constituents or the test will be invalidated. Fuel flow data shall be derived by measurement during the test for which emissions are to be calculated. Air flow data, preferably is from direct measurement but if such measurement is impractical, the data shall be taken from air consumption curves generated for the particular model of engine under test.

(c) Sample system contamination. (1) Care shall be taken to avoid loading of the sampling system with raw fuel discharge during engine starting.

(2) When the sample probe is in the exhaust stream and sampling is not in process, a back purge with air or an inert gas may be necessary to protect the probe and sample line from hydrocarbon buildup.

(d) Check sample line for contamination each time the instrument zero and span points are checked. Use the following procedure to check the sample line:

(i) Immediately after instrument zero and span measurements and necessary adjustments are complete, introduced hydrocarbon zero gas near the sample probe. If the instrument zero reading increases by more than 5 percent of the sample use in use the sample line shall be purged or cleaned as required, to bring the zero within limits.

(ii) When the requirements of paragraph (c) (2) (i) of this section have been met, introduce hydrocarbon span gas near the sample probe. If the instrument span reading is different by more than  $\pm 5$  percent from the correct setting for the scale in use, the sample line shall be purged or cleaned, as required to bring the span within limits.

[38 FR 19090, July 17, 1973; 38 FR 34784, Dec. 18, 1973]

#### § 87.97 Test run.

A test run shall consist of operating the engine in accordance with § 87.92. The engine shall be operated in the sequence called for under that section without intervening operating points unless an alternate procedure is agreed to in writing by the Administrator before such testing is conducted.

#### § 87.97 Chart reading.

Determine the HC CO, CO<sub>2</sub>, and NO<sub>x</sub> concentrations of the exhaust sample during the various modes from the instrument deflections or recordings made

in use of appropriate calibration charts. CO and CO<sub>2</sub> measurements shall be converted to wet basis by multiplying the recorded concentrations by a conversion factor calculated in accordance with good engineering practices for rich or lean mixtures as appropriate from air and fuel flow measurements or from

(a) HC mass/mode of ea. of the modes

Sum of the HC mass/mode of ea. of the modes  
Engine rated power (horsepower)

(b) Carbon monoxide:

CO mass/mode of ea. of the modes  
Sum of the CO mass/mode of ea. of the modes  
Engine rated power (horsepower)

(c) Oxides of nitrogen:

NO<sub>x</sub> mass/mode of ea. of the modes  
Sum of the NO<sub>x</sub> mass/mode of ea. of the modes  
Engine rated power (horsepower)

(d) The pollutant mass per mode shall be computed by use of the following formulas:

(1) HC mass/mode=HC emission rate  $\times$  TTM.

(2) CO mass/mode=CO emission rate  $\times$  TTM.

(3) NO<sub>x</sub> mass/mode=NO<sub>x</sub> emission rate  $\times$  TTM.

(c) The emission rates shall be computed by use of the following formulas:

(1) HC emission rate= $v_{exhaust} \times density_{HC} \times NO_{exhaust}$

(2) CO emission rate= $v_{exhaust} \times density_{CO} \times NO_{exhaust}$

(3) NO<sub>x</sub> emission rate= $v_{exhaust} \times density_{NO_x} \times NO_{exhaust}$

(d) The time-in-mode (TTM) shall be specified below (in minutes):

(1) Tad/Idle (out) ----- 12.0

(2) Takeoff ----- 0.3

(3) Climbing ----- 6.0

(4) Approach ----- 6.0

(5) Taxi/Idle (in) ----- 4.0

(6) CO emission rate=pounds/hour

of exhaust carbon monoxide emitted in an operational mode.

(7) NO<sub>x</sub> emission rate=pounds/hour of exhaust oxides of nitrogen emitted in an operational mode.

(8) V exhaust=Total engine exhaust volume flow rate in terms of cubic feet per hour at 68°F. and 760 mm. Hg pressure. V exhaust shall be calculated in accordance with good engineering practices from actual air and fuel flow measurements or from air consumption curves generated for the particular model of engine under test.

(9) (i) Density HC=Density of hydrocarbons in the exhaust gas, assuming an

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average carbon to hydrogen ratio of 1:1.85, in pounds per cubic foot at 68°F. and 760 mm. Hg pressure (0.0359 lb./cu. ft.).

(d) Density CO=Density of carbon monoxide in the exhaust gas in pounds per cubic foot at 68°F. and 760 mm. Hg pressure (0.0726 lb./cu. ft.).

(e) Density NOx=Density of oxides of nitrogen in the exhaust gas, assuming they are in the form of nitrogen dioxide in pounds per cubic foot at 68°F. and 760 mm. Hg pressure (0.119 lb./cu. ft.).

(f) HC conc.=hydrocarbon concentration of the exhaust sample in parts per million by volume.

(g) NOx conc.=Oxides of nitrogen concentration of the exhaust sample in parts per million by volume.

(h) TTM = Time in mode as specified in paragraph (d) of this section divided by 60 to yield time in hours.

[50 FR 19000, July 17, 1975, as amended at 52 FR 34724, Dec. 18, 1977]

**§ 87.100 Compliance with emission standards.** Compliance with emission standard under this part. The pollution level for the cycle shall not exceed the standard.

**Subpart J—Temporary Exemption From Aircraft Emission Standards (Fuel Venting and Smoke)**

**§ 87.101 Application for Temporary Exemption.**

(a) The Administrator shall publish in the *Federal Register* the name of the owner or operator to whom a temporary exemption is granted and the period of such exemption.

(c) No state or political subdivision thereof may attempt to enforce a standard respecting fuel venting or smoke emissions from an aircraft or engine if such aircraft or engine has been granted an exemption from such standard.

[50 FR 35001, Dec. 21, 1977]

**§ 87.102 Thirty-day suspension of fuel venting and smoke standards.**

(a) The applicability of the standards of § 87.11(a) and § 87.31(a) to aircraft subject to such standards is suspended until February 1, 1978.

(b) All good faith efforts to achieve compliance with such standard.

(c) A "p" which he will achieve in the shortest time

(b) Applications for temporary exemption from the requirements of § 87.31(a) shall be submitted in duplicate to the Administrator of the Environmental Protection Agency and shall contain the following information:

(1) The name and address of the applicant.

(2) The standard or requirement from which temporary exemption is requested.

(3) The number of aircraft or aircraft engines subject to the requirement for which a temporary exemption is requested.

(4) The efforts made by the applicant to accomplish compliance, including ordering of equipment and scheduling of maintenance work, and the dates of these efforts.

(5) A detailed statement of reasons why the applicant will not be in compliance when the standard or requirement becomes effective.

(6) The name of the equipment supplier and/or the name of the firm retained to perform the maintenance work.

(7) The applicant's proposed timetable for installation of equipment and obtaining necessary approvals for each aircraft or aircraft engine for which temporary exemption is requested, and the name of the person responsible for accomplishing compliance according to the timetable proposed by the applicant.

(c) Prior to taking action on an application for temporary exemption, the Administrator shall consult with the Secretary of Transportation. A copy of the applicant's request should be submitted by the applicant to the Secretary of Transportation.

(d) The Administrator shall publish in the *Federal Register* the name of the owner or operator to whom a temporary exemption is granted and the period of such exemption.

(e) No state or political subdivision thereof may attempt to enforce a standard respecting fuel venting or smoke emissions from an aircraft or engine if such aircraft or engine has been granted an exemption from such standard.

**§ 87.103 Application for Temporary Exemption.**

(a) The Administrator of the Environmental Protection Agency may grant to any aircraft or aircraft engine temporary exemption from any applicable standard under § 87.11(a) or § 87.31(a), provided that the owner or operator of such aircraft or aircraft engine demonstrates that the owner or operator of such aircraft or aircraft engine demonstrated compliance with such standard.

(b) Inability to comply with such standard, due to circumstances beyond his control, and

(c) A "p" which he will achieve in the shortest time

(b) Application for temporary exemption from the standards of § 87.11(a) and § 87.31(a) for aircraft which will not be in compliance in accordance with the procedures of § 87.101. [38 FR 35001, Dec. 21, 1977]

**APPENDIX A—INSTRUMENTATION (AIRCRAFT GAS TURBINE ENGINE MEASUREMENTS)**

(a) *NDIR* analyzers. Nondispersive infrared (*NDIR*) analyzers shall be used for the continuous monitoring of carbon monoxide and carbon dioxide.

The *NDIR* instruments operate on the principle of differential energy absorption from infrared beams of infrared energy. The energy is transmitted to a differential detector through parallel cells, one containing a reference gas, and the other, sample gas. The detector, charged ion, the component to be measured, transduces the optical signal to an electrical signal. The electrical signal thus generated is amplified and continuously recorded. The *NDIR* analyzer used in accordance with Subpart H of this part shall meet the following specifications:

(1) Response time (electrical). 90 percent full scale response in 0.5 second or less. Zero drift—Less than  $\pm 1$  percent of full scale in 2 hours on most sensitive range. Span drift—Less than  $\pm 1$  percent of full scale in 2 hours on most sensitive range. Repeatability— $\pm 1$  percent of full scale. Noise—Less than 1 percent of full scale on most sensitive range. Cell temperature—Minimum 50° C. maintained within  $\pm 2$ ° C.

(2) Range and accuracy.

*Accuracy excluding interferences*

Ranges

Carbon monoxide:

0 to 100 p.p.m.  $\pm 2$  percent of full scale  
0 to 500 p.p.m.  $\pm 1$  percent of full scale  
0 to 2500 p.p.m. Carbon dioxide:

0 to 2 percent  $\pm 1$  percent of full scale  
0 to 5 percent  $\pm 1$  percent of full scale

(3) All *NDIR* instruments shall be equipped with cells of suitable length to measure exhaust concentrations within the ranges encountered to the indicated accuracy. Range changes shall be accomplished either by the use of stacked sample cells or changes in the electronic circuitry, or both.

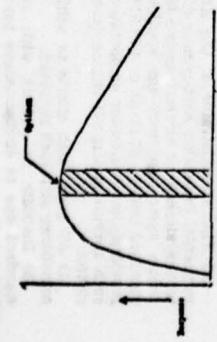
(b) Total hydrocarbon analyzer (1) General design specifications. The measurement of total hydrocarbon is made by an analyzer using a flame ionization detector (FID). With this type detector an ionization current, proportional to the mass rate of hydrocarbon entering a hydrogen flame, is established between two electrodes; the small current is measured by an electrometer amplifier and continuously recorded.

(c) Set oven temperature at 160°  $\pm 5$ ° C. Follow manufacturer's instructions for instrument startup and basic operating adjustment. Fuel shall be 60 percent helium, 40 percent hydrogen containing less than 2 p.p.m.c. hydrocarbon. Air shall be "hydrocarbon-free" grade containing less than 2 p.p.m.c.

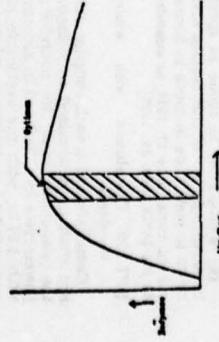
(d) Set oven temperature at 160°  $\pm 5$ ° C. Reach temperature for the system to equilibrates. The temperature is to be maintained at set point  $\pm 2$ ° C.

(e) Introduce a mixture of propane in air at a propane concentration of about 600 p.p.m.c. Vary the fuel flow to burner and determine the peak response. A change in zero may result from a change in fuel flow; therefore, the instrument zero should be checked at each fuel-flow rate. Select an operating flow rate that will give near maximum response and least variation in response with minor fuel-flow variations. A typical curve for response versus fuel flow is shown in the following figure.

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(d) To determine the optimum air flow, use fuel flow setting determined above and vary air flow. A typical curve for response versus air flow is shown in the following figure:



After the optimum flow settings have been determined, these flows are to be measured and recorded for future reference.

(ii) Oxygen/air. Check the response of the detector with varied concentrations of oxygen in the sample following the steps outlined below; this test shall be made with oven temperature at the set point and with gas flow to the detector at optimum conditions, as determined in paragraph (b) (1) of this section.

(a) Introduce nitrogen ( $N_2$ ) zero gas and zero analyzer; check zero using hydrocarbon-free air; the zero should be the same.

(b) The following blends of propane shall be used to determine the effect of oxygen ( $O_2$ ) in the sample.

Propane in  $N_2$  at 10%  $\pm 0.5\%$   $O_2$  and balance  $N_2$ .

Propane in zero grade air (refer to 18 FR 34734, Dec. 16, 1973).

(c) The volume concentration of propane in the mixture reaching the detector should be about 500 ppm  $C_3$ , and the concentration of both the  $O_2$  and hydrocarbon should be

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#### App. B

new, drawless stainless steel tubing resistance heated using a low voltage, high current power supply to a temperature of 600°C. This provides sufficient residence time at a sample flow rate of 700 cc. per minute (1.5 c.f.m.) for essentially complete conversion of nitrogen dioxide to nitric oxide. Other converter designs may be used if shown to yield equivalent results.

The difference between the response to propane in nitrogen and response to propane in a diluent containing 10 percent  $O_2$  shall not exceed 2 percent. If the 2 percent specification cannot be met by changing the sample flow rate or burner parameters, such as air and/or fuel-flow rate, the detector shall be modified or replaced.

(iii) Linearity and relative response.

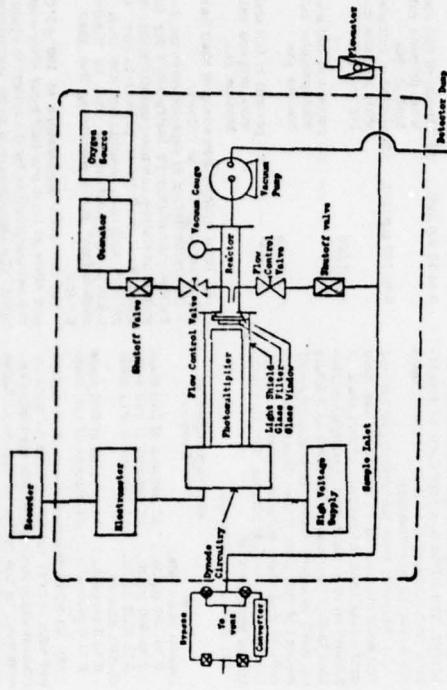
(c) With analyzer optimized in accordance with paragraph (b) (3) of this section, the instrument linearly shall be checked for the range covering the range of analysis using propane in air at nominal concentrations of 50, 60, and 90 percent full scale of each range. The deviation of a best-fit curve from a least-squares best-fit straight line should not exceed 2 percent of the value at any point. If this specification is met, concentration values may be calculated by use of a single calibration factor. If the deviation exceeds 2 percent at any point, concentration values shall be read from a calibration curve prepared during this alignment procedure.

(b) A comparison of responses to the different classes of compounds shall be made using (individually) propylene, toluene, n-hexane, and propane, each at 20 to 60 ppm  $C_6$  concentration in air. If the response to propylene, toluene or n-hexane differs by more than 6 percent from the response to propane, check instrument operating parameters. Reducing sample flow rate improves uniformity of response.

(c) Oxides of nitrogen analytical system. The chemiluminescence method utilizes the principle that nitric oxide ( $NO$ ) reacts with ozone ( $O_3$ ) to give nitrogen dioxide ( $NO_2$ ) and oxygen ( $O_2$ ). Approximately 10 percent of the  $NO$ , electronically excited. The transition of excited  $NO$  to the ground state, yields a light emission (600–2600 nanometer region) at low pressures. The detectable region of this emission depends on the  $Pt$ -tube/optical filter being used in the detector. The intensity of this emission is proportional to the mass flow rate of  $NO$  into the reactor. The light emission can be measured utilizing a photomultiplier tube and associated electronics.

(1) The method also utilizes the principle that the thermal decomposition of  $NO_2$  to  $NO + O_2$  is complete at about 600°C. The rate constant for the dissociation of  $NO_2$  at 600°C is approximately 10 (liters/mole-second). A 6-foot length of one-eighth inch outside diameter, 0.025 inch wall thickness

new, drawless stainless steel tubing resistance heated using a low voltage, high current power supply to a temperature of 600°C. Response time (2 to 4 sec. is typical) is primarily dependent on the mechanical pumping rate at the operating pressure of the reactor. The following figure is a flow schematic illustrating one configuration of the major components required for the oxides of nitrogen analytical system.



(2) The method permits continuous monitoring of NO<sub>x</sub> concentrations over a wide range. Response time (2 to 4 sec. is typical) provides sufficient residence time at a sample flow rate of 700 cc. per minute (1.5 c.f.m.) for essentially complete conversion of nitrogen dioxide to nitric oxide. Other converter designs may be used if shown to yield equivalent results.

(3) The oxides of nitrogen analyzer used in accordance with Subpart I of this part shall meet the following specifications:

Response time (electrical)—90 percent of full scale in 0.5 second or less.

Zero drift—Less than  $\pm 1$  percent of full scale.

Noise—Less than 1 percent of full scale.

Repeatability— $\pm 1$  percent of full scale.

(b) The FID analyzer used for measurement of hydrocarbons in accordance with Subpart I of this part shall meet the following specifications:

Response time (electrical)—90 percent of full scale in 0.5 second or less.

Noise— $\pm 1$  percent of full scale on most sensitive range.

Repeatability— $\pm 1$  percent of full scale.

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**Appendix B—Instrumentation (ANCAZT-Piston Engine Measurements)**

(e) The NDDE analyzer used for continuous monitoring of carbon monoxide and car-

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**Zero drift**—Less than  $\pm 1$  percent of full scale in 2 hours on all ranges.  
**Span drift**—Less than plus or minus of full scale in 2 hours.

**Linearity**—Response with propane in air shall be linear with  $\pm 2$  percent over the range of 0 to 20,000 p.p.m.C.

**Accuracy:**

0 to 100 p.p.m.C.  $\pm 5$  percent of full scale with propane calibration gas.

0 to 1,000 p.p.m.C.  $\pm 2$  percent of full scale with propane calibration gas.

0 to 10,000 p.p.m.C.  $\pm 1$  percent of full scale with propane calibration gas.

(c) The oxides of nitrogen analyzer used for measurement of oxides of nitrogen in accordance with Subpart I of this part shall meet the following specifications:

**Response time (electrical)**—90 percent of full scale in 0.5 second or less.  
**Noise**—Less than 1 percent of full scale.

**Repeatability**— $\pm 1$  percent of full scale.

**Zero drift**—Less than  $\pm 1$  percent of full scale in 2 hours.

**Span drift**—Less than  $\pm 1$  percent of full scale in 2 hours.

**Linearity**—Linear to within  $\pm 2$  percent of full scale on all ranges.

**Accuracy**— $\pm 1$  percent of full scale on all scales.

(d) The dynamometer, test stand, and other instruments for measurement of power output and air and fuel flow measurement instrumentation in accordance with Subpart I of this part shall be accurate to within  $\pm 2$  percent at all power settings.

**PARTS 88-99 [Reserved]**

## APPENDIX V

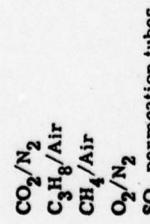
## REVIEW OF CALIBRATION SPAN GASES

Almost all analytical methods utilize span gases for calibration.

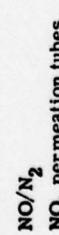
For example, a lack of consistency of NO (in N<sub>2</sub>) between five samples has been discovered by EPA. (230) The five NO in N<sub>2</sub> span gas bottles, all vendor certified at 715 ppm  $\pm$  1% were crosschecked for accuracy on several chemiluminescent and non-dispersive analyzers. These checks showed concentration ranging as high as 1200 ppm and as low as 500 ppm depending upon the bottle used as the span standard.

The Air Pollution Analysis Section of the Analytical Chemistry Division of NBS has been involved in developing standard reference gases.

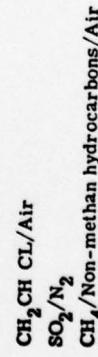
Hughes (231) reported that certain standard reference gases exist, such as mixtures of



Other standard reference gases are in preparation, such as



and still others are investigated as potential standard reference material, such as



Hughes (1974) states that the preparation of gas mixtures is not particularly difficult and the routine preparation of "standards" is commonplace. However, experience has shown that the accuracy of such standards is often woefully inadequate for the measurements for which the standards are intended. The major reasons for the inadequacy are the uncertainty in assigning an accurate value to the concentration and the uncertainty in the stability of the gas mixture storage and use.

Thus, NBS has been involved in the development of gaseous Standard Reference Materials which required the preparation of a series of primary standards and a deduction of the accuracy of the standards while simultaneously investigating the stability of the primary standards and of the particular gas mixture in the container in which it will eventually be distributed as a Standard Reference Material.

Hughes (1974) has described in some detail the preparation of carbon monoxide and nitric oxide standard reference materials. For example, difficulties of maintaining the original CO concentrations for a period of time is recognized. Some stainless steel cylinders have been found to induce unpredictable and "often disastrous reduction" in CO concentrations.

Similar problems can be encountered with NO. Hughes describes the NBS procedure for producing reference standard material for NO. From his description one can conclude that, concerning the nitric oxide mixtures, it appears that a stable series of standards at concentrations between 50 ppm and 1000 ppm can be provided. A maximum error of between  $\pm$  1 or 2 percent appears to be reasonable and the shelf life and quantity available appears to be adequate.

Gravimetric mixtures can be prepared with an error of about  $\pm 0.2$  percent relative. In a sample case the difference between samples approximated the imprecision in the measurement of the sample and the error in the gravimetric samples was considered to be this imprecision.

Hughes then describes the preparation of the test mixture. He states that the major source of error in the composition of mixtures generated by gas blending systems lies in the uncertainty in calibration of the flow measuring devices, i.e., the thermal conductivity type. A description of the calibration procedure is given in the following.

The estimated error in the calculated concentration of a mixture prepared by blending two streams of gas of known composition is about 0.8 percent relative. This is based on the uncertainty in the composition of the stream containing the nitric oxide (0.2 percent) and the errors in calibration of the flowmeters.

Table 3.1 is a summary of results obtained by Hughes using three methods. The calculated value is based on both the measured pressure and the measured weights. The analyzed value was obtained by measurement of the sample using a chemiluminescent analyzer calibrated with mixtures of nitric oxide generated by the dynamic dilution system. Hughes states that there is generally good agreement between all samples with the exception of the value calculated from the pressure data for sample #133. The agreement between the gravimetric result and the analyzer values suggest an error in reading or recording the pressure data for this particular sample.

The value assigned to the primary standards is the value calculated from the gravimetric data. The internal self consistency of the set of gravimetrics shown in Table 2.5 is used to describe the accuracy of these

TABLE 3.1. Summary of Results Obtained by Three Methods for Concentration of Nitric Oxide Standards

Mixture No.	Calculated Weight	Concentration Pressure	Observed Concentration
133	960.	(92)	962.
135	951.	951.	948.
140	949.	950.	948.
132	449.	445.	443.
142	451.	449.	447.
143	446.	446.	447.
131	225.	225.	221.
144	227.	227.	225.
145	226.	227.	225.
147	94.4	93.1	93.3
148	94.5	93.5	93.3
149	95.2	94.3	95.1
150	45.4	45.0	45.3
151	46.2	46.0	45.9
152	45.2	45.2	45.3

(All concentrations are in parts per million)

standards and the pressure data and analysis against the dynamic dilution standards is considered confirmatory.

Hughes then states the cylinders in which the Standard Reference Materials were packaged were first treated by soaking with a mixture of nitric oxide in nitrogen at about the concentration with which they were to be finally filled. All cylinders were new and unused and were carefully prepared by drying, evacuating, and flushing with oxygen-free nitrogen. The long term stability is expected to be adequate and will be confirmed by further analyses as described above.

The possibility of an increase in concentration due to desorption of nitric oxide is being investigated by analysis of a number of cylinders from each lot in which the pressure is decreased stepwise from 2000 psi to about 500 psi. Apparently, analyses often do not indicate that any serious desorption occurs but further analyses over a longer period of time will be necessary to confirm this. Several samples in each lot were examined for

other oxides in nitrogen. No evidence of any other oxides within the limits of precision of the measurement were observed. The limits of measurement for this analysis is considered to be about  $\pm 0.2$  percent relative. Each lot of fifty-three samples included five samples packaged in aluminum cylinders. It can be shown that the aluminum cylinders offer some advantage.

However, it is not possible to prepare standard reference materials for reactive gases. In that case permeation tubes must be utilized. They consist essentially of a tube of porous material, usually Teflon, containing a liquid such as sulfur dioxide or nitrogen dioxide. The material in the tube permeates through the walls of the tube at a rate determined by the vapor pressure of the substance, and at constant temperature the permeation rate is constant. The devices are used to generate atmospheres containing a known quantity of the substance by placing them at fixed temperatures in a stream of air or other gas flowing at a known rate.

Hughes states that to serve as a satisfactory standard a permeation tube must permeate at a predictable and unchanging rate throughout its useful lifetime. The rates are determined by measurement of the weight loss per unit time at a number of fixed temperatures. The tubes are calibrated by periodic measurement of the weight while maintaining the tube at a constant temperature. Permeation tubes must maintain a predictable rate even after subjection to varying temperature excursions both of use and storage.

Hughes then describes some of the difficulties encountered.

Nitrogen dioxide permeation tubes are not as predictable in use as sulfur dioxide tubes have proven to be, because the rate has been found to decrease significantly with time. This problem appears to lie in drying of the nitrogen dioxide with which the tube is filled and protecting the tube from subsequent exposure to high concentration of water vapor.

Nitrogen dioxide permeation tubes can be calibrated with an accuracy equal to sulfur dioxide tubes of similar output. However, greater caution must

be exercised when weighing tubes because of the hygroscopic nature of the external surface of the permeating area.

As in the case for reference standard materials, commercially available permeation tubes may show large variations. In a recent comparison with NBS certified tubes by McAdie and Hoplon (232) discrepancies of up to 55 percent were discovered.

## APPENDIX VI

### LIST OF COMMERCIALLY AVAILABLE POINT SAMPLERS

(From Air Pollution Equipment News, June 1977)

TABLE I: QUICK-REFERENCE SELECTION CHART

OPERATING PRINCIPLE												
	organic gases	inorganic gases	particulates	heavy metals	sampling method	instrument location	degree of automation	operator skill level	configurations available	power required	monitored air	services offered
AEROCHEM	CM				CT	LB OS	AU		SI		AM CS PS	
AIRFLOW DEVELOPMENT		AS PH			GS CT	OS	MA AU	SK	PA SI TA	AC	CS	
ANACON	CR IR UV	PH		PH	GS CT	LB OS	MA SA AU	US SK	PA SI	AC	AM CS PS	AP IN FS
ANALYTICAL INSTRUMENTS	CR	CM							SI	NE BT	AM CS PS	
ANTEK	CM CR		CM CR		GS CT	LB	AU	SS	PA	AC	AM	AP IN FS TK
APPLIED AUTOMATION	CR	CR		CR	CT				PA		CS PS	
APPLIED ELECTROCHEMISTRY		EC			CT	OS			SI		CS PS	
APPLIED RESEARCH			FL PH	FL PH	CT	LB	MA AU		SI		AM CS AP	
ARCAS	CR IR UV PH	CR IR UV			CT	OS	AU	US SK	PA SI	AC	AM CS PS	AP IN FS TK
BACHARACH	EC			UV	GS CT	OS	MA AU	SS	PA SI	BT AC	AM	AP FS
BAIRD ATOMIC				PH	CT	OS	AU	US	PA	AC	AM	AP IN FS
BASELINE	CR	CR			GS CT	LB CS	MA SA AU	US	PA SI	BT AC	AM CS PS	AP IN FS
BECKMAN	CR IR	CM CR EC WC			CT	LB OS	AU	SK	PA	AC	AM CS PS	AP IN FS TK
BGI	EC				GS CT	LB OS	MA	US SS	SI	BT	AM	IN FS
BIMARINE	EC	EC			CT	OS	SA AU		PA SI	NE AC	AM	AP
CALIBRATED INSTRUMENTS	IR	EC WC			CT	LB OS	MA AU	US SK	PA SI	NE BT	AM CS PS	AP IN FS
CARLE	CR	CR		CR		LB	MA AU		PA SI		AM CS PS	
CEA INSTRUMENTS	IR UV	EC IR UV WC			GS CT	LB OS	MA AU	US SS	SI	BT AC	AM CS PS	AP IN FS TK
CELESCO/BERKELEY		EC			CT	LB OS	MA SA	SS	PA SI	BT AC	CS PS	AP IN FS
CENTURY		CR				LB OS			PA	BT	AM	
CHEMICAL DATA SYSTEMS	CR	CR			GS	LB OS	MA SA AU	SS	PA	BT AC	AM CS PS	AP IN FS
CLEVELAND			PH		CT	OS	AU	SS	PA	AC	CS PS	AP FS
CLIMET			PH		GS CT	LB OS	MA SA	SS	PA SI	AC	AM	AP IN FS TK
CONTRAVES-GOERTZ			PH			OS			PA	BT	CS PS	
CONTROL INSTRUMENTS	EP				CT	OS	AU	SS	PA	AC	AM	AP FS
DACO	CR CL PH WC	CR CL PH WC			GS CT	OS	MA	US	PA SI	BT AC	AM CS AP	
DAVIS			PH			OS					CS	
DE-TEC-TRONIC			PH		CT	OS	SA AU	SS	SI	AC	CS PS	AP FS
DELPHI	CR				CT		AU		SI		AM CS PS	
DEVCO ENGINEERING	EC	EC			CT	LB	AU	SS	PA	NE AC	AM	
DICTAPHONE	EC				CT	OS	AU		SI	BT AC	AM	AP FS
DIONEX			CR		GS	LB OS	MA SA	US	PA	AC	AM	AP IN FS

## KEY TO ABBREVIATIONS

## OPERATING PRINCIPLE

AS ASSAY  
CL COLORIMETRIC  
CM CHEMILUMINESCENT  
CR CHROMATOGRAPHIC  
EC ELECTROCHEMICAL  
EP ELECTROPHYSICAL  
FL FLUORESCENT  
IR INFRARED  
NC NUCLEONIC  
PH PHOTOMETRIC  
UV ULTRAVIOLET  
WC WET CHEMICAL

## SAMPLING METHOD

CT CONTINUOUS  
GS GRAB SAMPLING

## INSTRUMENT LOCATION

LB LABORATORY  
OS ON-SITE

## DEGREE OF AUTOMATION

AU AUTOMATED  
MA MANUAL  
SA SEMI-AUTOMATED

## OPERATOR SKILL LEVEL

SK SKILLED  
SS SEMI-SKILLED  
US UNSKILLED

## CONFIGURATIONS AVAILABLE

PA PACKAGED ANALYZERS  
SI SENSING INSTRUMENTS  
TA TEST APPARATUS

## POWER REQUIRED

AC AC  
BT BATTERIES  
NE NON-ELECTRICAL

## MONITORED AIR

AM AMBIENT  
CS COMBUSTION EFFLUENT  
PS PROCESS EFFLUENT

## SERVICES OFFERED

AP APPLICATION/ENGINEERING  
FS FIELD SUPPORT  
IN INSTALLATION  
TK TURN-KEY

OPERATING PRINCIPLE									
	organic gases	inorganic gases	particulates	heavy metals	sampling method	instrument location	degree of automation	operator skill level	configurations available
DU PONT	CR	PH UV WC	PH UV	AS	GS CT	OS	MA AU	SK	PA SI BT AC AM CS PS
DYNAMATION	ECEP	EC			CT	OS	MA AU	US	SI BT AC AM AP FS TK
DYNATRON			PH		CT	OS	MA SA AU	SS	PA SI AC CS PS AP IN FS
EBI		EC			GS CT	LB OS	MA SA	SS	PA SI BT AM AP IN FS
ECA			PH		CT	OS	AU	SS	SI AC CS PS AP
ENMET	EP	EP			CT	OS	AU	US	SI BT AC AM CS AP FS
ENVIRONMENT-ONE	PH		PH		GS CT	LB OS	SA AU	US	SI BT AC AM AP
ENVIRONMENTAL PRODUCTS		EC PH			OS	AU	US	PA SI TA BT AC AM CS PS AP IN FS	
ENVIRONMENTAL SYSTEMS			IR		CT	OS	AU	US	SI AC CS PS AP IN FSTK
ECOM	IR	IR			CT	LB OS	AU	PA SI	AC AM AP IN FSTK
ERCOO	EP				CT	OS	AU	SI	BT AC AM PS FS
ERT					OS	SA AU		SITA	BT AC AM CS PS AP IN FSTK
ESI		EC			GS CT	LB OS	MA SA	US	PA SI NE BT AC AM CS AP IN FSTK
EXTECH	CR	CME CUV			GS CT	LB OS	MA AU	SS	PA AC AM CS AP IN PS FSTK
EXTRANUCLEAR LABS			EC			LB OS	MA SA AU	SS	PA SI AC AM CS PS AP IN FSTK
FINNIGAN	CL CR			CL CR	CT	LB		SI	AC AM PS
FISHER SCIENTIFIC	AS	AS CR	CL PH UV WC		GS	LB OS	MA	SS SK	TA BT AC AM AP IN FS
FRONTIER			PH			LB OS	SA	SS	SITA AC PS AP IN FSTK
GASTECH	UVEC	UVEC			CT	OS	AU	SS	PA SI BT AC AM AP IN FS
GCA			NC		GS CT	OS	MA SA AU	SS	PA SI BT AC AM AP IN FSTK
GENERAL MONITORS	EP	EP			CT	OS	AU	SS	PA SI TA BT AC AM AP FS
GOW-MAC	CR	CR			GS CT	LB	MA SA	SS SK	SI AC CS AP FS
GUBELIN	UV CL	CL	PH		CT	OS	AU	SS	SI AC AM CS PS IN FS TK
HNU	PH	PH			CT	LB OS	SA AU	US	PA SI BT AC AM PS AP FS TK
HONEYWELL	CR UV	CR PH			CT	OS	SA AU	SS	PATA AC AM CS PS AP IN FSTK
HORIBA	IR CR	CM			CT	LB OS	SA AU	SS	PA SI AC AM CS PS AP IN FS
HOUSTON ATLAS		CL PH			CT	LB OS	AU	SS	PA SI TA NE BT AC AM PS AP IN FSTK
IKOR			EP		GS CT	OS	MA SA AU	SS	PA AC CS PS AP IN FS
INFRARED	IR	IR			CT	LB OS	MA	US	PA SI AC AM CS PS AP FS
INTERSCAN		EC			CT	OS	SA AU	US	PATA BT AC AM AP FS
JACOBY-TARBOX			PH		CT	OS	AU		PA SI AC AM CS PS AP FS
KEVEX			CL	CL	GS CT	LB OS	MA SA AU	SS	PA SI AC AP IN FSTK
KVB		CM EC FL IR UV			CT	OS	MA SA AU		PA AC CS AP IN FSTK

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EP ELECTROPHYSICAL  
FL FLUORESCENT  
IR INFRARED  
NC NUCLEONIC  
PH PHOTOMETRIC  
UV ULTRAVIOLET  
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SI SENSING INSTRUMENTS  
TA TEST APPARATUS

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AC AC  
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## OPERATING PRINCIPLE

	organic gases	inorganic gases	particulates	heavy metals	sampling method	instrument location	degree of automation	operator skill level	configurations available	power required	monitored air	services offered
LA MOTTE	CL WC	CL WC	CL WC	CL WC	GS	OS	MA	US	PATA	NE BT	AM	AP
LEAR SIEGLER	UV	UV	UV		CT	OS	MAAU	SS	PASI	AC	AM CS PS	AP IN FSTK
LEEDS AND NORTHROP	EP CL	EP CL CR				LB OS			SI	AC	AM	
LUFT		WC		WC								
LUMIDOR	EC	EC			CT	OS	SA	US	SI	BTAC	AM	
MACLEOD AND STEWART			PH		CT		SA	SS	PA	AC	CS	AP IN FSTK
MAST		EC			CT	LB OS	AU	US	PA	BTAC	AM	AP
MATHESON	AS	AS PH		AS	GS CT	LB OS	MAAU	US		NE AC	AM CS	
MC MILLAN		CM			CT	LB OS	SAAU	SS	PATA	BTAC	AM CS PS	AP IN FS
MDA	PH	PH			CT	OS	MASA	SS	PA	BTAC	AM	AP IN FSTK
MELOY LABORATORIES	CR	FL PH CM			CT	LB OS	MASA AU	SS	PASI	BTAC	AM CS PS	AP FS
MET ONE			PH		CT	LB OS	AU		SI	BTAC	AM	AP IN FSTK
METRONICS				CL	GS	LB OS	MASA AU	SS	TA	BTAC	AM CS PS	AP IN FS
MILTON ROY	CL	CL			CT	OS	SAAU		PASI	BTAC	CSPS	APFS
MOCON	IR	IR			GS CT	LB OS	SA	SS	SITA	BTAC	AM	AP IN FS
MONITOR LABS		CM PH			CT	LB OS	AU	SS	PA	AC	AM CS PS	AP IN FSTK
MRI			PH		CT	LB OS	MASA AU	SS	SI	BTAC	AM CS PS	AP IN FSTK
MSA	CR IR	CR IR			GS CT	LB OS	MASA AU	SS	PASI	AC	AM CS PS	APFS
NICOLET	AS IR	AS IR	AS IR		GS CT	LB OS	SAAU	SK	SI	AC	AM CS PS	AP IN FSTK
NUCLIDE	CR CL	CR CL		CR CL NC	GS CT	LB AU	MASA AU	SS SK	PATA	AC	AM	AP IN FS
NUTECH	AS CREC WC	AS WC	AS WC		GS CT	OS	MASA	SS	PASI TA	BTAC	AM CS PS	AP
PETROLITE				EC	GS	LB	SA	SS	SI	AC	PS	APFS
PGT		FL	FL		CT	LB			PA		AM PS	
PHILIPS		WC			CT		MASA AU	SS	PA	AC	AM	IN FS
PHOTOBELL			CL PH EP		CT	OS	AU	SS	SI	AC	AM CS PS	AP
PHOTOMATION			PH		CT	OS	AU		PA	AC	CSPS	APFS
PRECISION SCIENTIFIC		CL			CT	OS	SAAU	US	PA	NE AC	AM	
RAC	WC	CL EC FL PH UV UV WC	EC PH UV		GS CT	LB OS	MASA AU	SS SK	PASI TA	NE BT AC	AM CS PS	AP IN FS
RADIAN	CR IR	CM CL FL UV WC	AS PH	AS PL	GS CT	LB OS	MASA AU	SS SK	PASI	NE BT AC	AM	AP IN FSTK
RAEKO	CR	CM EC FL IR UV			CT	OS	SA	SS	PASI TA	NE BT AC	AM CS PS	AP IN FSTK
RELIANCE			PH			OS			PA		CS	
SCOTT	AS IR CL	AS CM IR EP			GS CT	LB OS	MASA AU	SS	PASI TA	AC	AM CS PS	
SGA		CM			CT				PA		AM CS PS	
SNAP-ON	IR	IR				OS			PA		CS	
TAYLOR	EP	EP			GS CT	LB OS	AU		PA	BTAC	CSPS	APFS
TECH ECOLOGY			PH			LB OS					AM	
TECHNICON	CL WC	CL WC			GS	LB OS	AU	SS	PA	AC	AM	AP IN FS
TELEDYNE ANALYTICAL	CL	CL			CT	LB OS	AU		PASI	AC	AM CS	
THERMCO		EP			CT	OS	AU	SS	PA	AC	AM CS PS	AP IN FSTK
THERMO-ELECTRON		CM PL			CT	LB OS	MASA AU	SS	PASI	AC	AM CS PS	AP IN FSTK
THETA		EC			GS CT	LB OS	MA	SS	PASI	BTAC	AM CS PS	AP IN FSTK

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MANUFACTURER		CR			GS CT	LB OS	MA AU	SS			CS	AP IN FSTK
TUDOR	CR CL WC	CR CL WC	CR CL WC		GS CT	LB OS	MA	SS SK	PATA	NE		
UNITED TECHNICAL	CR	CR	EC FL PH		GS	LB OS	MA SA	SS	PASI TA	BTAC	AM CS PS	AP IN FSTK
VARIAN	CR	CR		PH	GS	LB AU	SS	PA	AC		AM CS PS	
WAGER			PH		CT	OS	SA	SS	SI	BTAC	CS PS	APP S
WARD	CL				GS CT	LB OS		US	PA	NE	AM	
WESTERN PRECIPITATION		EC	PH		GS CT	OS	MA SA AU	SS SK	PASI TA	BTAC	AM CS PS	AP IN FS
WESTERN RESEARCH & DEVELOPMENT	CR	AS CM CR CL IR UV WC	AS	WC	GS CT	LB OS	MA AU	SS SK	PASI TA	AC	AM CS PS	AP IN FSTK
WESTINGHOUSE		EP				LB OS	AU		SI	AC	CS PS	
WHITTAKER		EC	EC		CT	OS			PASI	AC	AM	
XONICS	CR	PHCM			CT	LB OS	SA AU	SS	PA	AC	AM	AP IN FSTK

## KEY TO ABBREVIATIONS

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 CL COLORIMETRIC  
 CM CHEMILUMINESCENT  
 CR CHROMATOGRAPHIC  
 EC ELECTROCHEMICAL  
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 FL FLUORESCENT  
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 NC NUCLEONIC  
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SAMPLING METHOD  
 CT CONTINUOUS  
 GS GRAB SAMPLING  
  
 INSTRUMENT LOCATION  
 LB LABORATORY  
 OS ON-SITE  
  
 DEGREE OF AUTOMATION  
 AU AUTOMATED  
 MA MANUAL  
 SA SEMI-AUTOMATED

OPERATOR SKILL LEVEL  
 SK SKILLED  
 SS SEMI-SKILLED  
 US UNSKILLED  
  
 CONFIGURATIONS AVAILABLE:  
 PA PACKAGED ANALYZERS  
 SI SENSING INSTRUMENTS  
 TA TEST APPARATUS  
  
 POWER REQUIRED  
 AC AC  
 BT BATTERIES  
 NE NON-ELECTRICAL

MONITORED AIR  
 AM AMBIENT  
 CS COMBUSTION EFFLUENT  
 PS PROCESS EFFLUENT

SERVICES OFFERED  
 AP APPLICATION/ENGINEERING  
 FS FIELD SUPPORT  
 IN INSTALLATION  
 TK TURN-KEY

## APPENDIX VII

## DERIVATION OF SIGNAL-TO-NOISE RATIO

## EQUATIONS AND ERROR ANALYSIS

**APPENDIX VII****DERIVATION OF SIGNAL-TO-NOISE RATIO  
EQUATIONS AND ERROR ANALYSIS**

In this appendix we derive a generalized set of SNR expression for remote monitors, discuss some of the fundamentals in statistical error analysis and consider questions in instrument accuracy.

**Derivation of Signal-to-Noise Equations**

The accuracy with which a physical quantity  $x$  can be observed experimentally is given by

$$\text{SNR} = \frac{x}{dx} \quad (\text{VII-1})$$

where  $dx$  is the error (or noise) of  $x$ . When the quantity  $x$  depends on the variables  $y_i$ , the total error is determined on the principle of superposition of errors<sup>(162)</sup>, which is given by the total error differential, viz.,

$$\begin{aligned} dx &= \frac{\delta x}{\delta y_1} dy_1 + \frac{\delta x}{\delta y_2} dy_2 + \dots \\ &= \sum_i \frac{\delta x}{\delta y_i} dy_i \end{aligned}$$

where  $dy_i$  are the errors for each variable  $y_i$ . The most probable value of  $dx$  is the square root of the sum of the squares of the individual errors. Thus,

$$(dx)_{rms} = \sqrt{\left(\frac{\delta x}{\delta y_1} dy_1\right)^2 + \left(\frac{\delta x}{\delta y_2} dy_2\right)^2 + \dots}$$

and

$$SNR = \frac{x}{(dx)_{rms}} = \frac{1}{\sqrt{\left(\frac{\delta x}{\delta y_1} \frac{dy_1}{x}\right)^2 + \left(\frac{\delta x}{\delta y_2} \frac{dy_2}{x}\right)^2 + \dots}}$$

(VII-2)

$$= \frac{1}{\sqrt{\frac{1}{(SNR)^2 y_1} + \frac{1}{(SNR)^2 y_2} + \dots}}$$

The limiting sensitivity of a system that measures the quantity  $x$  is given by Eq. (VII-2) and setting SNR to unit, viz.,

$$(x)_{SNR=1} = (dx)_{rms}$$

where  $(x)_{SNR=1}$  is called the "noise-equivalent-quantity  $x$ ". (Typical examples are noise-equivalent-radiance [NEN], noise-equivalent-temperature [NET], noise-equivalent-concentration [NEC], noise-equivalent-power [NEP], etc.)

We will now give several examples in which the quantity  $x$  is substituted by different physical parameters.

Example 1. The physical parameter to be measured is the radiant power  $P$  from a source. Assuming there are no variables influencing  $P$ , then  $x = P$  and  $dx = dP$ . The noise  $dP$  is generally composed of three components: The shot noise due to the arrival of signal photons, the background noise and the detector noise; i. e.,  $\left(\frac{h\nu}{\eta t_g} P\right)^{1/2}$ ,  $\left(\frac{h\nu}{\eta t_g} P_B\right)^{1/2}$ , and NEP, respectively. The square of the noise is then given by<sup>(111)</sup>

$$(dP)^2 = \left(\frac{h\nu}{\eta t_g} P\right) + \left(\frac{h\nu}{\eta t_g} P_B\right) + (\text{NEP})^2 \quad (\text{VII-3})$$

where  $h$  is the Planck constant,  $\nu$  is the frequency at which the radiant power  $P$  is observed,  $\eta$  is the quantum efficiency of the detection system and  $t_g$  is either the gate time, integration time or pulse width,  $P_B$  is the radiant power of the background and NEP is the noise-equivalent-power due to the detector. The magnitude, and thus the significance, of the noise components is different in the UV and IR portions of the spectrum because of the different types of detectors used. In the UV, where usually photomultipliers are employed, the first component is always significant and the second one is significant only for long integration times. The third term (noise due to the dark current of the PM tube) can be neglected. In the IR, where photoconductors are used, the first term may always be neglected and the second one may or may not be important. The third term is always important, unless of course the background term is dominating.

Thus, for example 1, the appropriate expression for the signal-to-noise ratio is

$$\text{SNR} = \frac{P}{(dP)_{\text{rms}}} = \frac{P}{[(P + P_B) \frac{h\nu}{\eta t_g} + (\text{NEP})^2]^{1/2}} \quad (\text{VII-4})$$

If one can neglect the background noise, the SNR in the UV becomes

$$\text{SNR} = \sqrt{P \eta t_g / h\nu} \quad (\text{VII-5})$$

and in the IR becomes

$$\text{SNR} = \frac{P}{\text{NEP}}$$

Example 2. The physical parameter  $x$  is to be determined by the sum or difference of two measured signals. Thus,

$$x = P_1 \pm P_2$$

$$dx = dP_1 \pm dP_2$$

The most probable error is given by

$$(dx)^2 = (dP_1)^2 + (dP_2)^2$$

With the reasonable assumption that  $dP_1 \approx dP_2$ , the SNR becomes

$$\text{SNR} = \frac{P_1 \pm P_2}{\sqrt{2} dP} \quad (\text{VII-6})$$

Example 3. The physical parameter  $x$  is to be determined by the ratio of two measured signals:

$$x = P_1/P_2$$

$$dx = dP_1/P_2 - P_1 dP_2/P_2^2$$

The most probable error is given by

$$(dx)^2 = \left(\frac{P_2 dP_1}{P_2^2}\right)^2 + \left(\frac{P_1 dP_2}{P_2^2}\right)^2$$

For the case of  $dP_1 \approx dP_2$ , the SNR becomes

$$\text{SNR} = \frac{P_1 P_2}{dP \sqrt{P_1^2 + P_2^2}}$$

Example 4. The physical parameter  $x$  is to be determined by the  $\ln$  of the ratio of two signals, as in a transmission experiment. Thus

$$e^x = P_1/P_2$$

$$x = \ln P_1 - \ln P_2$$

$$dx = dP_1/P_1 - dP_2/P_2$$

The most probable error is given by

$$(dx)^2 = (dP_1/P_1)^2 + (dP_2/P_2)^2$$

Again, in case of  $dP_1 \approx dP_2$ , the SNR becomes

$$\text{SNR} = \frac{\ln P_1/P_2}{dP \sqrt{(1/P_1)^2 + (1/P_2)^2}} \quad (\text{VII-8})$$

For small  $x$  (i. e., almost transparent atmosphere),  $P_1 \approx P_2$ . Thus,

$$\ln P_1/P_2 \approx P_1/P_2 - 1$$

and

$$\text{SNR} \approx \frac{P_1(P_1 - P_2)}{dP \sqrt{P_1^2 + P_2^2}} \approx \frac{P_1 - P_2}{dP \sqrt{2}} \quad (\text{VII-9})$$

Equation (VII-8) may be expanded for the application of a pulsed system, where the signals are composed of the difference of two signals observed at two different times. Thus,

$$\text{SNR} = \frac{\ln P_1 P_2' / P_2 P_1'}{dP \sqrt{(1/P_1)^2 + (1/P_1')^2 + (1/P_2)^2 + (1/P_2')^2}} \quad (\text{VII-10})$$

### Accuracy Considerations

Dieck and Elwood<sup>(247)</sup> have formalized their approach to accuracy analysis which they first reported on in 1974<sup>(238)</sup>. Their analysis is based upon the statistical approach outlined by Natrelle<sup>(248)</sup>. We will follow here their analysis.

There are two basic types of errors: Bias (or systematic) errors and precision errors. Bias error is a measure of the deviation of the average from the true value  $x_t$ . Precision error is a measure of the instrument repeatability, i. e., the scatter about the biased average. The two errors are described mathematically by

$$\text{Bias error } b = \bar{x} - x_t$$

$$\text{Precision error } \sigma = \sqrt{\sum_i (x_i - \bar{x})^2 / (n-1)}$$

where  $n$  is the number of measurements and  $\bar{x}$  is the mean value of  $x$ . A graphical representation is given in Figure VII-1.

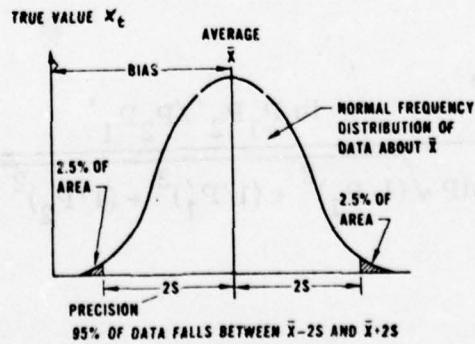


Figure VII-1. Effect of Bias and Precision Errors.

Therefore, the precision error is given by the mean deviation of the normal distribution of data about  $\bar{x}$ . The normal frequency distribution or Gauss distribution is given by<sup>(162)</sup>

$$y = \frac{1}{\sigma \sqrt{2\pi}} e^{-\frac{(x-\bar{x})^2}{2\sigma^2}}$$

The area under this curve, extending from  $-\infty$  to  $+\infty$ , is normalized so that the probability that an observation will lie between two values  $x_1$  and  $x_2$  is represented by the area under the curve between  $x_1$  and  $x_2$ , i.e.,

$$\frac{1}{\sigma \sqrt{2\pi}} \int_{x_1}^{x_2} e^{-\frac{(x-\bar{x})^2}{2\sigma^2}} dx$$

writing  $\xi = (x - \bar{x})/\sigma$

$$\xi_1 = (x_1 - \bar{x})/\sigma$$

$$\xi_2 = (x_2 - \bar{x})/\sigma$$

the integral becomes

$$\frac{1}{\sqrt{2\pi}} \int_{\xi_1}^{\xi_2} e^{-\frac{1}{2}\xi^2} d\xi$$

This integral can be expressed as the difference of two integrals of the type

$$\frac{1}{\sqrt{2\pi}} \int_0^t e^{-1/2\xi} d\xi$$

This integral has been evaluated for different values of  $t$ . It should be noted that the function

$$\frac{1}{\sqrt{\pi}} \int_{-t}^t e^{-\xi^2} d\xi = \frac{2}{\sqrt{\pi}} \int_0^t e^{-\xi^2} d\xi = \text{erf}(t)$$

is known as the error function. Thus,

$$\frac{1}{\sqrt{2\pi}} \int_0^t e^{-1/2\xi^2} d\xi = \frac{1}{\sqrt{\pi}} \int_0^{t/\sqrt{2}} e^{-\xi^2} d\xi = \frac{1}{2} \text{erf}(t/\sqrt{2})$$

Representative values of  $\text{erf}(t/\sqrt{2})$  are given below:

$t$	$\text{erf}(t/\sqrt{2})$
0	0
0.6745	0.5
1.0	0.6827
2.0	0.9543
3.0	0.9973
$\infty$	1.0

Therefore, one can see that in a normal distribution the probability that an observation lies within  $\pm 2\sigma$  of  $\bar{x}$  is 0.9543. Of particular interest is the value  $\bar{x} \pm 1.96\sigma$  for which  $\text{erf}(t/2) = .95$ , the so-called 95% confidence interval.

Dieck and Elwood show as an example the propagation of bias and precision errors through several levels of a calibration hierarchy (see Figure VII-2). The top level of uncertainty is the National Bureau of Standards,

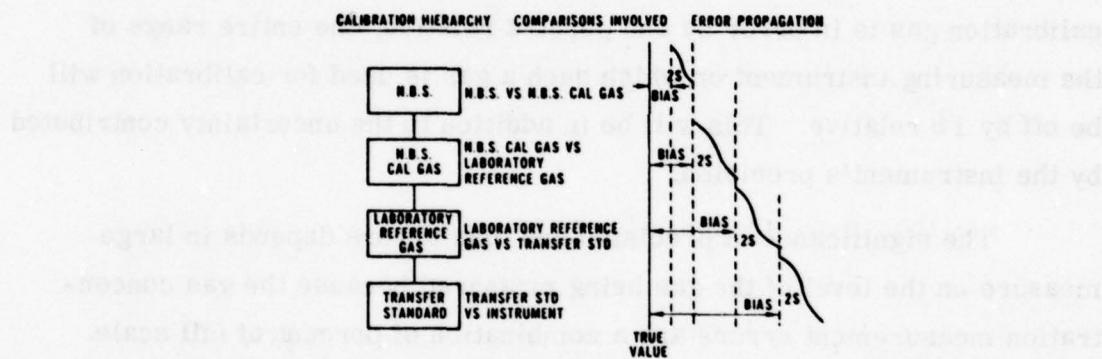


Figure VII-2. Propagation of Error in a Calibration Hierarchy.

the second level, the National Bureau of Standards' supplied laboratory reference gas. The third level is the transfer standard calibration gas which, after comparison to the laboratory reference, is used to calibrate the instruments on the fourth level (i. e., the measuring instruments used). The precision of the fourth level is referred to as the calibration-to-calibration precision. Where NBS standard reference materials are not available, the problem of ascertaining the accuracy of the first level becomes even more complex.

Fundamental to the assessment of instrument accuracies is the proper choice of units: should accuracy be described as percent of point (a relative basis) or percent of full scale (an absolute basis). Data with normally distributed errors permit the use of terms such as precision and variance in a way in which they are generally understood and clearly defined. Dieck and Elwood suggest the use of percent of full scale units as the best units for the instruments' precision errors.

Bias errors, however, should be expressed as relative errors because they are largely a result of calibration gas uncertainty. If a calibration gas is in error by one percent relative, the entire range of the measuring instrument on which such a gas is used for calibration will be off by 1% relative. This will be in addition to the uncertainty contributed by the instrument's precision.

The significance of precision and bias errors depends in large measure on the level of the gas being measured because the gas concentration measurement errors are a combination of percent of full scale and percent of point error. The instrument errors are percent of full scale, one value to be utilized over an entire instrument range. They usually dominate the errors on the lower half of an instrument range. Calibration gas errors are percent of point and, therefore, depend on the level of the gas concentrations being measured. Calibration gas bias errors usually dominate on the upper half of an instrument's range.

By evaluating the precision with which an instrument repeats when reading the calibration gas, an estimate may be had of the instrument's precision when reading a test point. Calibration precision is utilized because the calibration gas concentration is assumed invariant (for the duration of a test) thus placing all variations as instrument caused.

Dieck and Elwood found a considerable variability in instrument precision from day to day and range to range. The existence of the variability, however, requires the evaluation of the instrument precision on the day when field tests are to be undertaken. Dieck and Elwood state that daily precision error estimates must be combined with calibration gas uncertainties for the proper expression of emission measurement accuracies. In Table VII-1 they compare the Environmental Protection Agency's required emission instrument precisions with those typically obtained in use. For most cases for which there is some comparison, typical in use, in day precision is worse than that required by the EPA.

TABLE VII-1 Comparison of EPA Required Instrument Precisions—  
Those Typically Obtained In-Use in One Day.

Constituent	Range	In-use precision	EPA required precision
CO <sub>2</sub>	0-2%	0.02%	0.02%
	0-5%	0.09%	0.05%
CO	0-100 ppm	3.0 ppm	1.0 ppm
	0-500 ppm		5.0 ppm
	0-1000 ppm	19.6 ppm	10.0 ppm
	0-2500 ppm		25.0 ppm
HC	0-10 ppm C		0.1 ppm
	0-100 ppm C	4.0 ppm	1.0 ppm
	0-1000 ppm C	22.0 ppm	10.0 ppm
	0-2000 ppm C	20.0 ppm	20.0 ppm
NO <sub>x</sub>	0-200 ppm NO <sub>x</sub>		2.0 ppm
	0-500 ppm NO <sub>x</sub>		5.0 ppm
NO	0-200 ppm NO	5.0 ppm	2.0 ppm
	0-500 ppm NO		5.0 ppm
NO <sub>2</sub>	0-200 ppm NO <sub>2</sub>	5.0 ppm	2.0 ppm
	0-500 ppm NO <sub>2</sub>		5.0 ppm

The authors state further that "EPA parameters such as accuracy and precision were not well defined in their regulations; it is assumed here that the precision required is  $2\sigma$  over the 95% confidence interval. This precision comparison underscores the need for continued, current evaluation of emission instrument performance and the need to recognize the possible difference between typical in-use precision and that required by the EPA."

## APPENDIX VIII

### METEOROLOGICAL INSTRUMENTS FOR USE IN THE CALIBRATION TEST RANGE

## APPENDIX VIII

### Meteorological Instruments for Use in the Calibration Test Range

relatively short moment arm. In addition, friction has been reduced by utilizing miniature ball bearings and special type transmitters. The cups are generally 5 cm. in diameter and have a moment arm of about 7 cm. By using six staggered cups, a greater surface area is exposed to the wind. This factor decreases the starting threshold from .75 mph (.35 m/s) for the standard 3-cup anemometer to .4 - .5 mph (.2 - .25 m/s). This design also produces a more uniform torque around the entire shaft revolution.

In order to describe fully the atmospheric environment in a calibration test range for remote sensors, the wind velocity (direction and speed), the humidity, temperature, precipitation, and solar radiation must be known accurately. A description of available instrumentation techniques is given in the following (Adopted from Ref. 233). Additional information may be found in Refs. 234-238.

#### Wind Speed Sensor

Rotational anemometers (vertical and horizontal) are the most common type in use today mainly because they are the only types that satisfy all of the following desirable operational features: (1) Essentially linear relationship between the sensor output and the wind speed; (2) Calibration is unaffected by changes in the temperature, pressure or humidity of the atmosphere; (3) Able to measure a wind range of wind speeds (<2 to 200 mph); (4) Long term calibration stability. The calibration often is unchanged after 10 years continuous operation; (5) Output of the sensor is easily adapted to remote indication; (6) Recording of the wind speed data is easily adaptable to either analog or digital form; (7) Generally require extremely little maintenance. Light weight vertical shaft anemometers were developed for air pollution meteorology. To provide accuracy at low speeds and sufficient sensitivity, these small 3-cup anemometers are light-weight in construction (plastic or very thin aluminum) and employ a

one that has a propeller on the end of a horizontal shaft that is oriented into the wind by a vane on the opposite end of the shaft. The propeller is usually helicoidal in design, with the rate of rotation of the propeller being linearly proportional to the wind speed. The more sensitive propeller anemometers utilize lightweight aluminum or plastic as blade material, and generally employ either 2 or 4 blades. The 2-bladed propellers have starting speeds of about .4 - .7 mph (.2 - .35 m/s), while the 4-bladed propellers have a threshold of about .3 - .5 mph (.15 - .25 m/s).

In order to convert the rotation to an energy form that is transmittable, four types of transducers are in use; the D. C. generator, the A. C. generator, a light chopper and mechanical contact.

Small, permanent field D. C. generators are used that have an output which is linearly proportional to the rate of turning of the cup or propeller and, hence, is linearly proportional to the wind speed. The output from this transducer can be recorded directly on any D. C. galvanometer recorder. The main disadvantage of D. C. generators is the relatively high starting or threshold speeds. The brush and bearing friction combine to produce a lower limit to the threshold speed of about 1 mph (.5 m/s) on the most sensitive systems. The brushes on these generators usually need servicing only about once a year under continuous use.

## VIII b

In an attempt to lower the threshold speed by eliminating brush friction, A. C. generators are used instead of D. C. generators. A. C. generators reduce the friction considerably and eliminate brush and commutator maintenance. A. C. generators are available with either two, four six, or eight-pole permanent magnet rotors. The larger the number of poles, the more pulses are available per shaft revolution, producing a smoother record.

The largest disadvantage of the A. C. generator is associated with the number of pulses per shaft revolution. These pulses must be rectified for recording. Low wind speeds generate a low frequency of A. C. pulses and normal rectifiers do not function properly with a low frequency input and spurious oscillations may be produced. Therefore, to obtain wind speeds below about 2 m/sec (4 mph) some sort of electronic correction is needed. This disadvantage defeats the purpose of reducing the friction and has therefore resulted in a minimal use of this type of transducer.

Further reduction in friction with accompanying lower threshold speed and quicker response can be accomplished with the use of an interrupted light beam (light chopper) transducer. This transducer employs either a slotted shaft, a slotted disc, a light source and a photocell, or photo-diode. The cup or propeller rotates the slotted shaft or disc and a pulse is created each time a slot allows light from the source on one side of the shaft or disc to fall on the photocell on the other side of the shaft or disc. The larger the number of slots in the shaft or disc, the smoother will be the output, especially at low wind speeds. The output from the transducer is handled in the same manner as the output from the A. C. generator. The large number of slots (about 100) prevent spurious oscillations in the output at low wind speeds.

All of the measuring transducers mentioned so far produce an analog signal. There are circumstances where the desired output might be total miles of wind passage instead of a time plot of wind speed. Under these circumstances, a mechanical-contact transducer is used. In this type of

transducer, the anemometer shaft is connected through one or more gears to a cam or similar device that opens or closes a contact after the passage of a pre-determined amount of air. This contact closure can operate a readout device such as an event marker pen on a recorder. Recorders can be furnished with circuitry to provide a pen actuation for each 10, 100, or 1000 contact closures in the transducer. If the average wind speed is desired instead of length of wind passage, the number of contact closures are determined for a given time increment and, knowing the miles or meters of wind passage for each contact closure, the average wind speed over the given time increment is easily determined.

There are a number of other devices such as pressure anemometers, hot wire and sonic anemometers. But they all have disadvantages which have prohibited so far their use in operational type situations.

#### Wind Direction Sensors

These are made up of vanes of different configurations. The flat plate vane can take on a number of different shapes and be made out of a number of different materials. As with wind speed sensors, the material used in constructing the wind vane will generally determine the proper use of the vane. Vanes made out of heavy gauge metal or plastic can be used only for obtaining average wind direction. The large mass creates a high moment of inertia which will give, under certain conditions, a much higher indication of wind fluctuations than actually exists. The light-weight sensitive vanes have tails made out of thin gauge aluminum or plastic or molded expanded polystyrene. The counterweights are also close to the center of rotation. This design creates a highly sensitive vane that can be suitably used for turbulence measurements.

In the splayed vane, two flat plates are joined at a small angle (usually about  $15^{\circ}$ ) at one end of the horizontal shaft. This design came about through experimentation that showed that the splayed vane followed small changes in wind direction better than the flat plate. However, the increased mass incurred by two flat plates makes this type of vane unsuitable for anything but the measurement of average wind direction.

The aerodynamic shaped vane has an airfoil cross section. This type of vane has been shown to produce up to 15% more torque for certain ranges of attack angles than a flat plate vane of similar physical dimensions. This type of design, as with the splayed vane, incorporates more mass than the flat plate vane and therefore produces a higher moment of inertia, yielding a poor dynamic performance.

The bidirectional vanes are designed to rotate around a vertical axis to measure the azimuth angle of the wind, as does a conventional wind vane. It also can move in the vertical to measure the elevation angle of the wind. Because the vertical motions of the atmosphere are frequently of a different character than the horizontal motions (anisotropic turbulence), measurement of both the horizontal and vertical motions are desirable. This is particularly true under stable conditions when the vertical motion is almost absent, but horizontal changes in wind direction may be appreciable. Micropotentiometers are usually used to produce an analog record of both angles. The total wind speed can be measured by replacing the counterweight with a propeller anemometer.

The measurement of wind direction consists of converting the angular position of the wind vane to an energy form that can be transmitted easily. The sensitive wind direction systems usually employ a potentiometer system, or a synchro-motor system.

The most common and inexpensive way of converting the angular position of the vane to an electrical signal is through the use of a potentiometer system. In this system the shaft of the vane is attached to the wiper arm of the potentiometer. The swinging vane therefore produces a continuously varying voltage that can be recorded on a recording voltmeter or dial indicator. With proper calibration, the recorded voltage gives a direct reading of the angular position of the vane. The biggest drawback to this system is the unavoidable discontinuity in the potentiometer. If the wind direction is oscillating about a direction corresponding to this gap, the voltage output will oscillate between the maximum and minimum value. There are some types of recorder pen movements available that circumvent this problem. The use of micro-potentiometers produces the lowest moment of inertia of any of the direction transducers available today. This fact has led to their widespread use in the sensitive wind vanes that are noted for their good dynamic performance.

This transducer system consists of two synchronous motors wired so that any movement by the shaft of the transmitter will be duplicated by the shaft of the receiver motor, usually to an accuracy of about  $2^{\circ}$ , provided the lead resistance is kept to a maximum of 20 ohms. The vane shaft is coupled to the shaft of the transmitter motor and the shaft of the receiver motor is coupled to a recorder pen or some other read-out indicator. Therefore, any vane movement is duplicated by a movement of the dial needle, recorder pen, etc., and with proper calibration and alignment, a direct indication of wind direction is obtained. There is no discontinuity in the movement as with the potentiometer. The only disadvantage of this

transducer system is the relatively large moment of inertia of the motor assembly. This produces a poorer dynamic performance than the micro-potentiometer system and limits their use to the more rugged vane types.

#### Temperature Lapse Rate

The vertical structure of temperature gives an indication of the stability and turbulence of the atmosphere. One method of estimating the vertical structure of temperature is by measuring the difference in temperature between sensors mounted at different heights. This, of course, gives an average condition between any two particular sensors. Because of the pronounced influence of the earth's surface on the atmosphere's temperature, it is desirable to measure temperature difference at closer intervals near the ground than at higher levels. Resistance thermometers of copper or nickel may be used for temperature difference systems. Thermocouples of copper-constantan or iron-constantan also make reliable sensors. Resistance thermometers and thermocouples do not have to be frequently calibrated. Thermistors are more variable from unit to unit and they require recalibration more frequently than the other two types of sensors. Rapid response is usually not desired in measuring temperature differences.

Rather, averages on the order of 5 minutes are desired. If the sensors are 1/2 to 5/8 inch in diameter, they will respond slowly enough to give an average temperature. Precautions must be exercised in the shielding and ventilating of temperature sensors. (234-237)

The method of radiosonde (radio-soundings) observations is used routinely for temperature, pressure and humidity soundings of the upper air. A free balloon carries the sensors and a radio transmitter aloft. Cycling from sensor to sensor is by means of an aneroid barometer and consequently is a function of pressure. Observations are normally made twice daily at 0000 GCT and 1200 GCT at approximately 70 stations in the contiguous U. S. The ascent rate of the balloon is about 1000 ft./minute.

Generally only four to six temperature readings are recorded within the lower 3000 feet so the vertical temperature information is not too detailed. It is still of considerable use when more detailed information is not available.

#### T-Sonde consists of a temperature sensor and radio transmitter

which is carried aloft by a free rising balloon. The main difference between this system and the radiosonde system is that only temperature is measured. Ten to twelve measurements are taken within the lower 3000 feet of the atmosphere, thus giving more detailed structure of temperature with height. Using a captive balloon system to make vertical temperature measurements has the advantages of complete recovery of all components of the system, and as detailed a temperature sounding as is desired may be made by control of the level of the sensor. A balloon having fins is much easier to control and gives greater lift in slight winds than a spherical balloon. Most kite balloons can be used in winds less than 15 knots. For air pollution meteorology purposes, the light wind periods are of greatest interest. Because of hazards to aircraft, prior permission from the FAA is required for flights exceeding 500 feet above ground. For additional precautions when using captive balloons, see references 234-237.

Several methods of relaying the observations to the ground have been used. Using a wiresonde, a resistance thermometer is carried aloft by a kite balloon whose mooring cable contains wires connecting the sensor with a wheatstone bridge on the ground which is used to measure the resistance. Another system uses a modified radiosonde transmitter to measure temperature and humidity. The signal is transmitted to the ground receiver and recording equipment by the same method used in the radiosonde. Cycling from one sensor to another by a battery driven timing device. The temperature sensor is shielded from the sun by the styrofoam plastic and is aspirated by a small motor driven fan. The mooring of this system is by nylon cable marked at intervals to indicate the height of the sensor.

#### Rain Gauge

The standard rain gauge consists of a metal funnel 8 inches in diameter, a measuring tube having 1/10 the cross-sectional area of the funnel, and a large container of 8 inches diameter. Normally precipitation is funneled into the measuring tube. The depth of water in the tube is measured using a dip stick having a special scale (because of the reduction in area). Measurements with this instrument, since they are made manually, give only accumulation since the last measurement.

The recording or weighing bucket rain gauge does give detailed time resolution of occurrence, and amount of precipitation, as a strip chart, with one revolution per day, is used. The gauge consists of a bucket, to hold the precipitation, on a scale, which weighs the precipitation and moves the pen arm, recording the total accumulation on the chart which is calibrated in inches.

Tipping bucket rain gauge has a bucket with two compartments beneath the collecting funnel. When one side of the bucket collects a given amount (usually 0.01 inch) of precipitation, the bucket tips and empties the precipitation, collecting the next portion in the other side. The bucket movements are recorded on a chart. The number of bucket movements and the time they occur indicate the rainfall amount and rate.

#### Humidity

Because of its influence upon certain chemical reactions in the atmosphere and its influence upon visibility and thus atmospheric transmittance, it is mandatory to measure the humidity.

The hygrothermograph measures both temperature and humidity, activating pen arms to give a continuous record of each element upon a strip chart. The chart generally can be used for seven days. The humidity

sensor generally used is human hair which lengthen as relative humidity increases and shorten with humidity decreases. Temperature measurements are usually made with a bourdon tube, a curved metal tube containing an organic liquid. The system changes curvature with changes in temperature, activating the pen arm.

Humidity measurement by a psychrometer involves obtaining a dry bulb temperature and a wet bulb temperature from a matched set of thermometers. One thermometer bulb (wet bulb) is covered with a muslin wick moistened with distilled water. There must be enough air motion to cause cooling of the wet bulb due to evaporation of the water on the wick. A motor driven fan can be used to draw air at a steady rate past the moistened wick while a reading is taken. A sling psychrometer has both thermometers mounted on a frame which is whirled through the air to cause cooling by evaporation. Relative humidity is determined from the dry and wet bulb readings through the use of tables. Continuous measurements of humidity are not obtained using psychrometers.

## **APPENDIX IX**

### **ELECTROMAGNETIC INTERFERENCE CHARACTERISTICS REQUIREMENTS FOR EQUIPMENT**

**APPENDIX IX**

**Electromagnetic Interference Characteristics Requirements  
for Equipment**

(The following is an extract from pertinent U. S. Government specifications.)

**(4.) GENERAL REQUIREMENTS**

**(4. 1) Application of Standard.** - The requirements of this standard shall be applied to electronic, electrical and electromechanical equipment as indicated hereinafter:

**(4. 1. 1) Equipment.** - The requirements of this standard shall be applied to units or equipments that are intended to operate as individual items. Individual equipment classes are defined in Table I. Application of each test requirement for the particular equipment class is shown in Table II.

**(4. 1. 2) Government Furnished Equipment.** - Equipment furnished by the Government to a contractor may, unless the test data is furnished by the Government, require testing by the contractor for conformance to the equipment item class and limit requirements. Application of suppression measures to meet the requirements shall be detailed in the control plan.

(4.1.3) Commercial Off-the-Shelf Equipment. -

(4.1.3.1) When commercial off-the-shelf equipment is selected by the contractor all applicable tests required by this standard shall be performed and the test data submitted to the procuring activity to determine the EMI/EMC suitability in the end-item configuration. The EMI/EMC suitability shall be covered in the control plan (see 4.2).

(4.1.3.2) When C-E equipment certified to FAA Technical Standard Orders (Part 5.1.4 (a) and (b) are used with, or become part of any military equipment configuration, the requirements in 4.1.3.1 apply.

(4.1.3.3) Electrical and electromechanical equipment, not intended for use in tactical or critical military areas, are exempt for meeting the requirements of this standard unless specifically required by the procuring activity. When this equipment is procured for use in an unknown installation or for use in both tactical and nontactical installations the requirements stated in 4.1.3.1 shall apply.

(4.1.4) Reprocurements of equipments designed to superseded documents. - Production type equipments (all classes) designed prior to the effective date of this standard and certified to superseded specifications or standards shall meet the appropriate requirements specified in Appendix A of this standard.

(4.1.5) Other EMI Requirements. -

(4.1.5.1) If an equipment has met other emission and susceptibility requirements the test procedures and report may be submitted for evaluation by the procuring activity as evidence of meeting equivalent portions of this standard.

(4.1.5.2) All equipments, other than Class I equipment, produced by a manufacturer, which are identical to those previously produced by the same manufacturer, tested in accordance with this standard and found satisfactory shall require minimal testing, as indicated in the approved test plan, to ascertain conformance with this standard. A copy of the previous test report shall be forwarded with the new test report for comparison and evaluation.

(4.1.6) Short-Duration Interference. - Short duration interference is not exempt from the requirements of this standard, unless specifically indicated in the individual equipment specification. The short-duration interference requirements given in Appendix A shall be used for procurements of equipments designed to superseded documents.

**(4.1.7) Application of Standard for GSA Procurements.** - The interpretation of and recommendations for compliance approvals to the requirements of this standard, as applied in GSA procurements, may be directed to the preparing activity of this standard.

**(4.2) Interference Control Plan.** - The interference control plan shall be a detailed plan outlining the interference control or reduction program, the engineering design procedures and proposed techniques that will be used to determine conformance with the requirements of this standard and that will enable the equipment to perform its operational function without interference from its parts and subassemblies. Approval of the control plan and compliance thereto does not relieve the contractor of the responsibility of meeting the applicable requirements of this standard. Technically justifiable deviations which are being, or are to be formally processed through contractual channels may be included in the control plan.

Additional information on the preparation of the interference control plan may be found in the section on "Interference Control" (4.1.8).

**(4.3) Antenna System.** - The antenna system shall consist of the antenna, feed horn, and supporting structure. The antenna shall be designed to meet the requirements of the applicable standard for the type of antenna selected. The antenna shall be located in such a manner as to minimize interference with other equipment and to provide maximum gain in the direction of the intended receiver.

**(4.4) Radio Frequency Components.** - The radio frequency components shall consist of the transmitter, receiver, and associated control equipment.

**(4.5) Power Supply.** - The power supply shall consist of the power source and the power distribution system.

**(4.6) Grounding.** - The equipment shall be grounded in accordance with the applicable standard for the type of equipment.

**(4.7) Safety.** - The equipment shall be designed to meet the requirements of the applicable standard for safety.

**(4.8) Environmental Protection.** - The equipment shall be designed to meet the requirements of the applicable standard for environmental protection.

**(4.9) Reliability.** - The equipment shall be designed to meet the requirements of the applicable standard for reliability.

**(4.10) Maintenance.** - The equipment shall be designed to be easily maintained.

TABLE I - CLASSES OF EQUIPMENT

Class No.	Description
I	Communication-Electronic (C-E) Equipment Any item, including subassemblies and parts, serving functionally in electromagnetically generating, transmitting, conveying, acquiring, receiving, storing, processing or utilizing information in the broadest sense. Sub classes are:
IA	Receivers Using Antennas
IB	Transmitters Using Antennas
IC	Non-Antenna C-E Equipment (such as counters, oscilloscopes, signal generators, rf and audio test equipment, computers, power supplies, digital equipment, electrically operated cameras and projectors, wire terminal image interpretation facilities, photographic processing equipment and other electronic devices working in conjunction with classes IA and IB).
ID	Electrical and electronic equipment and instruments which would affect mission success or safety if degraded or malfunctioned by internally generated interference or susceptibility to external fields and voltages such as autopilots, infrared devices, flight instruments, auto-compasses and electronic engine control devices).
II	Non-Communication Equipment, Specific subclasses are:
IIA	Non-Communication-Electronic Equipment - Equipment in which rf energy is intentionally generated for other than information or control purposes. Examples are ultrasonic equipment, medical diathermy equipment, induction heaters, rf stabilized arcwelders rf power supplies and uninterruptible power units (both rotary and solid state).
IIB	Electrical Equipment - Some examples are electric motors, hand tools, office and kitchen equipment, laundry and repair shop equipment, and lithographic processing equipment.
IIC	Accessories for Vehicles and Engines - Electrically and mechanically driven and engine electrical accessories such as gauges, fuel pumps, regulators, windshield wipers, turret motors, magnetos and generators, when tested off of the vehicle or engine. Applicable only to accessories for use on items of classes IIIA and IIIB.
III	Vehicles, Engine-Driven Equipment

Table III - Test Requirements Applicable to Equipment Classes (Note 1)

	Equipment Class												Notes
	I A	I B	I C	I I A	I I B	I I C	I I I A	I I I B	I I I C	I I I D	I V	V (15)	
CE01	Y	Y	Y	N	N	N	N	N	N	N	N	N	30 Hz to 20 kHz, Power Leads 0.03 to 20 kHz, Control and Signal Leads
CE02	Y	Y	Y	N	N	N	N	N	N	N	N	N	0.02 to 50 MHz, Power Leads 0.02 to 50 MHz, Control and Signal Leads
CE03	Y	Y	Y	Y	Y	Y	N	N	N	N	N	N	(2, 6, 11)
CE04	Y	Y	Y	N	N	N	N	N	N	N	N	N	30 Hz to 50 MHz, Inverse Filter Method
CE05	Y	Y	Y	Y	Y	N	N	N	N	N	N	N	10 kHz to 12.4 GHz, Antenna Terminal
CE06	Y	Y	N	N	N	N	N	N	N	N	N	N	0.03 to 50 kHz, Power Leads 0.05 to 400 MHz, Power Leads
CS01	Y	Y	Y	Y	Y	N	N	N	N	N	N	N	30 Hz to 10 GHz, Intermodulation
CS02	Y	Y	Y	N	N	N	N	N	N	N	N	N	30 Hz to 10 GHz, Rej. of Undes., Sig. (2-SIG Gen Method)
CS03	Y	Y	N	Y	N	N	N	N	N	N	N	N	(7)
CS04	Y	Y	N	Y	N	N	N	N	N	N	N	N	30 Hz to 10 GHz, Cross- Modulation
CS05	Y	Y	N	N	N	N	N	N	N	N	N	N	Spike, Power Leads Squinch Circuits
CS06	Y	Y	Y	N	N	N	N	N	N	N	N	N	30 Hz to 10 GHz, Rej. of Undes., Sig. (1-SIG Gen Method)
(T) CS07	Y	N	Y	N	N	N	N	N	N	N	N	N	(7)
CS08	Y	N	Y	N	N	N	N	N	N	N	N	N	0.03 to 30 kHz, Magnetic Field 14 kHz to 10 GHz, Electric Field
RE01	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	(5)
RE02	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	10 kHz to 40 GHz, Spurious and Harmonics, Radiated Technique
RE03	N	Y	N	N	N	N	N	N	N	N	N	N	0.02 to 50 kHz, Magnetic Field 150 kHz to 1 GHz Vehicles and Engine Driven Equipment
(T) RE04	Y	Y	N	Y	N	N	Y	Y	Y	Y	Y	N	(10, 14)
RE05	N	N	N	N	N	N	N	N	N	N	N	N	Overhead Power Line Test
RE06	N	N	N	N	N	N	N	N	N	N	N	N	
RS01	Y	Y	Y	N	N	N	N	N	N	N	N	N	0.03 to 30 kHz, Magnetic Field Magnetic Induction Field
RS02	Y	Y	Y	Y	N	N	N	N	N	N	N	N	14 kHz to 10 GHz, Elect. Field
RS03	Y	Y	Y	Y	N	N	N	N	N	N	N	N	(17)
(T) RS04	Y	Y	Y	Y	N	N	N	N	N	N	N	N	14 kHz to 30 MHz

Y = Test shall be performed as described in MIL-STD-462 or the approved test plan.  
 N = Test does not have to be performed, unless required by the test plan or procuring activity.

**Notes for Table II:**

- (1) The test methods in MIL-STD-462 are designated by a series of numbers as shown hereinafter:

C = Conducted

R = Radiated

E = Emission

S = Susceptibility

"--" = Numerical order of test from 01 to 99.

T = New or Modified Test Procedure included for trial use, or as required by the procuring activity.

- (2) For Class IIIB items exceeding 600 volts AC or DC this test is not mandatory unless required by the procuring activity.
- (3) RE03 shall be performed when the operating frequency of the test sample is greater than 1.25 GHz, when the average power of the test sample is greater than 5 kW, or when the test sample's antenna is an integral part of the transmitter and cannot be replaced by a suitable dummy load.
- (4) Test method (CEO5) may be submitted to the command or agency concerned for approval in the test plan, in lieu of CE01, CE02, CE03, or CE04 when the signal to be measured is generated by a single shot event or at repetition rates of less than 5 pps.
- (5) These tests (RE01), (T) RE04 and RS01) shall be performed on equipment operating at frequencies up to 30 MHz. Equipment operating at higher frequencies are exempt from testing.
- (6) For classes II B, IIC, IIIA and IIIB perform the test over the frequency range of 150 kHz to 50 MHz. For class IIIB only, remove the 10 microfarad feed-through capacitor.
- (7) Perform either CS04 or CS08, as approved in the test plan.
- (8) Shall conform to F. C. C. Regulations, Part 15 or Part 18 as applicable. In addition, the applicable requirements of this standard shall be met for ultrasonic equipment, rf power supplies and uninterruptible power units (both rotary and solid state).
- (9) Class II A shall be tested from 14 kHz to 20 kHz with this test procedure (CE01). However, when required by the individual equipment specification, the test shall be performed from 1 kHz to 20 kHz.

- (10) For class IIIC items, this test is not required above 400 MHz.
- (11) Electric hand tools (which fall under class IIB) shall be tested from 150 kHz to 30 MHz in accordance with the requirements and procedures of Method A-CE1 as specified in the Appendix to this standard.
- (12) Class IIB items, except electric hand tools, shall be tested from 150 kHz to 400 MHz. Electric hand tools shall be tested from 150 kHz to 30 MHz. Class IIIC items shall be tested from 150 kHz to 1000 MHz.
- (13) Class IIID items shall comply with the requirements of SAE J551.
- (14) For class IIIB items exceeding 240 kVA, this test is not mandatory unless required by procuring activity or project manager.
- (15) These requirements are applicable for all MEP sets having outputs 240 kVA or less. When specified by the command or agency concerned MFP sets having power outputs greater than 240 kVA shall meet the requirements of RE02.
- (16) For Class V items, this requirement is applied between 14 kHz and 1000 MHz at a test distance of 1 meter. If test conditions preclude performing RE02 at a 1 meter distance, a distance of 6 meters may be used and the limit curve in Figure 26 corrected accordingly.
- (17) For Class V items with electronic circuitry for external regulation or control or sets with amplifiers for electronically controlling regulation, temperature, frequency, stability, and so forth, this requirement is applied between 2 MHz and 10 GHz in addition to CE03 and RE02.